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STATE REGULATION OF ELECTRICITY SUPPLY TARIFFS: RECENT GERMAN LEGISLATION COMPARED WITH BRITISH TENDENCIES

By J. W. BEAUCHAMP, Member,* and R. KAUFFMANN, Companion.†

(*Paper first received* 4*th February, and in revised form* 21*st February*, 1939; *read before* THE INSTITUTION 30*th March, before the* SOUTH MIDLAND CENTRE 3*rd April, and before the* WESTERN CENTRE 3*rd April*, 1939.)

SUMMARY

The authors give particulars of recent State action in Germany and France for the standardization of electric supply tariffs.

Typical stages of domestic electrification in Germany and Britain are compared with the cost of the supply to consumers.

German practice in regard to hire-purchase of apparatus, account collections, and undertakers' rate commitments, is discussed.

Current tariff practice in Great Britain is reviewed, with its results to date and the probable interaction between charges and load growth. Consideration is given to the extent to which a unification of charging methods could be applied without restricting the competition between electricity and other forms of heat energy for use in the home, the probable extent of this application in the future, and its relative importance in relation to the magnitude and costs of public supply.

As in most other European countries, a definite tendency towards unification of methods of charging for electricity supplies had been spreading in Germany, not by way of direct legislative interference by the State, but through the influence of the professional associations and the large territorial bulk-supply undertakings. The advantages of two-part tariffs had become generally realized, and the number of suppliers without such tariffs has been comparatively small in recent years. But uniformity did not go much further than this, and the complaints of consumers and public bodies in regard to undue differences between local tariffs have been as lively in Germany as in other European countries.

In consequence of this the ground was well prepared psychologically for official interference on sweeping lines, the more so as strong measures of unification in all fields play a prominent part in home politics in Germany.

On these premises the Reich Commissioner for Fixing Prices (Der Reichkommissar für die Preisbildung) published a decree dated 25th July, 1938, under the title of "A Decree on the Formation of General Tariff Prices for the Supply of Electrical Energy." On the same day a first executing decree was issued and the Economic Group for Electricity Supply (Wirtschaftsgruppe Elektrizitätsversorgung), a public body under which the whole electricity supply industry is compulsorily organized, communicated these two decrees to its members, together with a covering circular dated 8th August, 1938. This circular is based on the text of the decrees and on the explanations given to the Group by the Reich Commissioner. It is published with the Reich Commissioner's consent and is therefore to be considered as of equal binding power with the decrees themselves. The following presentation of the new order in German electrical economy is based on the combination of these three regulations, which, for simplicity's sake, will be called the "New Rules."

It may be said here that, contrary to the proposals of the McGowan report, the New Rules do not in any way tend to an amalgamation of existing undertakings; although the number of such undertakings in Germany is about equal to that in Great Britain, the influence of the large territorial bulk-suppliers made such measures appear to be not very urgent in the case of Germany. On the other hand the New Rules embrace all sales by all public suppliers with regard to the following classes of consumers:—

(1) Domestic.
(2) Commercial lighting.
(3) Small industrial power.
(4) Rural.

In other words the New Rules affect practically all the l.t. consumers; they do not say so in so many words, but the limitation to l.t. consumers is implied. It is part of the Rules to establish just these four classes of l.t. consumers, and further subdivisions are not encouraged. For all other business, particularly for h.t. supplies, the liberty of the suppliers is not interfered with, barring an important exception in the matter of bulk supplies.

The Rules are all governed by one guiding principle—the compulsory introduction for the above classes of customers of a two-part (or rather an all-in) tariff, or, to be quite exact, of two such tariffs at the option of the consumer, one with a higher, the other with a lower fixed charge, these fixed charges to be absolutely comprehensive and to include the costs of metering, accounting, etc. The authors will discuss later in the paper the lines on which these fixed charges must be established according to the Rules; fundamentally the supplier is completely bound as to the forms permitted, and is as completely free regarding the amount of the fixed charge in the case of each individual undertaking.

The distinguishing factor between the two tariffs is the unit price. Two maxima of 8 and 15 pfennig respectively (1·6d. and 3d. at the new parity, and 1d. and 2d. at the old parity) are imposed. A flat-rate tariff (with certain qualifications) must be offered as an alternative to the smallest consumers, including those with a low utilization of their installation, and it will thus

* Formerly with Central Electricity Board.
† Formerly with Bewag, Berlin.

be seen what a very much simplified frame the German suppliers have from now on in which to build their tariffs. The ultimate date by which all undertakings have to adopt the Rules has not yet been published. At present the only date mentioned is the 1st January, 1939, on which all suppliers of over 300 000 units a year had to adapt their rural tariffs. In all other respects suppliers are instructed to start immediately on the preparation of the new tariffs and to speed up the change-over by every possible means. All new tariffs under the New Rules must be submitted to the Reich Commissioner for his consent before publication. This is apparently only an administrative regulation; as a matter of fact it is perhaps the second fundamental point in the New Rules, because the ruling of the commissioner will have a much stronger unifying effect than the mere wording of the Rules.

Of the two components of the two-part tariff, the running charge is regulated in much the less detail. The undertakings are allowed to go below the prescribed maximum of 15 and 8 pfennig; they are, however, expected to maintain a reasonable relation between the two unit charges. Of the two tariffs, the one with the lower running charge is definitely compulsory. As regards the 15-pfennig tariff the undertakings are advised by the Circular that they can get special consideration on application in those cases where the 15-pfennig price is not likely to offer new advantages to the consumer. The option between the two tariffs must be absolute, and no staggering of the running charge is permissible on any pretext whatsoever.

The establishment of the fixed charge for *domestic* use is based exclusively on the number of rooms; it is to be borne in mind that Germans are in general flat-dwellers and that the flats are standardized to a considerable extent. The rules for establishing the number of rooms are as follows:—

All habitable rooms and one kitchen per household may be counted as rooms, irrespective of the presence of electrical installation in such rooms. On the other hand the following rooms must not be taken into account:—

(1) Rooms of less than 6 m^2 surface. The undertakers can increase this figure according to the particular conditions in their area with a view to finding the most advantageous solution for the customer.

(2) Corridors, lobbies, open balconies, bathrooms, lavatories, basements, attics, wash-houses, wood and coal cellars, boiler rooms, linen cupboards, and similar rooms.

(3) Garages for private use.

(4) Rooms used for agricultural purposes, housing animals, storage, such as stables, granaries, etc., with the proviso that stables over 50 m^2 can be charged as one room for every 50 m^2 above the first 50.

So far as the Rules do not expressly mention particular kinds of rooms the supply undertakers are advised to exclude expressly such extra rooms as are usual in their territory.

So far as staircases are concerned, it is recommended that private staircases should be charged as one room; in blocks of flats, for staircases and other rooms in common use, such as wash-houses, courtyards, and so on, the domestic tariff is not applicable. In this case the commercial lighting tariff should be used.

The Circular states that if the power installed is disproportionately small compared with the number of habitable rooms, the consumer can be referred to the flat-rate tariff exclusively.

For commercial lighting and small industrial power, the basis of assessment is principally demand, with an alternative possibility for lighting (see below). The demand can be computed from the power installed or from the actual maximum demand or power contracted for. The unit employed is either the kilowatt or the kilovolt-ampere. All details are left to the discretion of the supply undertaking. In the case of small industrial consumers with a greater number of motors or other apparatus, some reduction for any motor in excess of one is decreed, particularly in those cases where all motors cannot be used at the same time.

While these Rules apply both to commercial lighting and to small industrial power, another basis is laid down for commercial lighting only, i.e. the size of rooms, alone or in combination with the other principles. So far as size of rooms is the basis of assessment, the rules prescribe a division of rooms into classes, and this is explained by the first executive decree and the Circular as follows:—

At least three classes must be formed, viz.:—

Class I. Shops, stores, workshops and rooms in hotels, boarding-houses, etc.

Class II. Rooms in assembly halls and storage rooms.

Class III. Stables and similar places.

For each of these classes a definite size of area must be established as a unit, and the fixed charge for the unit must be the same in all classes. It is admissible to subdivide the rooms in question into more than three classes; if the supplier keeps to the three official classes the unit must be at least 10 m^2 in Class I, 20 m^2 in Class II, and 25 m^2 in Class III. The suppliers can increase the figures to suit their requirements. The Circular recommends that advertising lighting should be governed by the unit principle and that a certain figure of installed watts of such lighting should be counted as a unit.

The suggestions given for a combined demand and area charge go into so much detail that to set them out would cause this paper to exceed the limits allowed.

For rural consumers both the demand and the area principle are applicable, but these consumers must be given a further option based on area in agricultural use. Furthermore, the agricultural consumer can obtain separate accounts for his household according to the two other possibilities. In so far as the agricultural user wishes to pay according to the agricultural area, the assessment unit is the hectare (2·47 acres). In this case woods, streams, lands, heaths, grazing land, and similar land, must not be included. If the farmer is using part of his space for industrial purposes the supplier may assess these as industrial power.

While the two-part tariff formed on the lines now expounded is the regulation tariff, in a few cases the New Rules admit other forms of tariff. An ordinary

flat-rate tariff is to be optionally offered to all domestic consumers who come under the heading of very small consumers, or consumers with small utilization of their installation. There is no more accurate definition of these concepts, and according to the Circular it is more or less left to the consumer's common sense whether he will describe himself as a very small consumer and apply for the flat rate. The flat-rate tariff may also be combined with the two-part tariff in such a way that at the end of each year the consumer is charged either on the original flat rate or on the two-part tariff, whichever is the more favourable to him.

The supplier is authorized to levy a small fixed charge in this case also, but this fixed charge must not cover more than the actual cost of metering and accounting.

It is further made compulsory to offer to all consumers an off-peak price of not more than 4 pfennig a unit. This tariff is meant for the promotion of all appliances

Table 1

DOMESTIC CONSUMPTION IN GREAT BRITAIN (1938–39)

Type of consumption	Range of annual consumption (kWh) of:—		
	Wage-earning class	Higher spending power (1) class	Higher spending power (2) class
Lighting			
(1) Functional	150–200	300–400	400–600
(2) Decorative (*a*)			—
Power			
(3) Suction cleaner, (4) Washing machine, (5) Fans		75–150	100–200 (*a*)
(6) Refrigerator			300–500
(7) Miscellaneous small appliances		25–25	50–50
Heating			
(8) Flat iron	50–75	50–75	25–50 (*a*)
(9) Drying cupboard, (10) Miscellaneous small appliances			100–300
(11) Kettle, (12) Cooker (*b*)	800–1 000	800–1 000	800–1 000 (*a*)
(13) Wash boiler (*b*)	200–250	200–250	200–250 (*a*)
(14) Water heater (*b*) (sink and lavatory basin), thermostatic control	1 000–1 500	1 000–1 500	2 000–3 000
(15) Bath heater (thermostatic control) (*c*) (*b*)		2 000–3 000	3 000–6 000
(16) Bath heater (hand control) (*c*) (*b*)	750–1 250	—	—
(17) Centralized water-heating (*b*)		As Nos. 14 + 15 + losses	
(18) Fires (radiant), (19) Heaters (convective) (*b*)	250–400	250–500 (*b*)	3 000–6 000 (*b*)
Communications			
(20) Bells, (21) Clocks		0–25	25–50
(22) Radio receivers	50–75 (*b*)	50–75 (*b*)	50–75 (*b*)
	3 250–4 750	4 750–7 000	10 050–18 075
General range, say, kWh p.a.	3 000–5 000	5 000–7 000	10 000–18 000
Assumed rental or rateable value	£20–£30	£50–£70	£120–£160
Fixed charge, based on 10 % of R.V.	£2–£3	£5–£7	£12–£16
Consumption, at 0·5d. per kWh	£6 5s. to £10 8s. 4d.	£10 8s. 4d. to £14 11s. 8d.	£20 10s. 8d. to £39
Total cost	£8 5s. to £13 8s. 4d.	£15 8s. 4d. to £21 11s. 8d.	£32 10s. 8d. to £55
Cost per week	3·16s. to 5·2s.	5·95s. to 8·35s.	12·5s. to 21·0s.

(*a*) In class (2) and households of still higher spending power there is great variation, and averages are of little value. In this class also there is greater use of outside services, e.g. laundry, restaurants.
(*b*) Considerable variation in consumption, particularly in winter, depending on fuel heating equipment installed.
(*c*) Control of hours of heating by supplier not appreciably affecting consumption per annum.

consuming off-peak current. The suppliers are therefore advised to fix the hours for this tariff so that reasonable use can be made of such appliances.

The supplier can either charge the whole consumption within the off-peak hours on this tariff, or he can limit this price to the use of certain appliances specified by him. In all these cases the supplier is entitled to increase the fixed charge by an amount which will cover the special metering instruments installed, or he can impose a minimum consumption for a given time or appliance. Where the consumption of a definite appliance can be gauged with sufficient certainty, a lump-sum tariff may be offered. This lump-sum tariff is of an optional character.

Some general rules are to be applied to all tariffs. The consumers are obliged to give to their suppliers all information necessary for the establishment of their fixed charge, and to inform them of any alteration of conditions which might imply an alteration of the fixed charge. So far as options are offered, the consumer is bound to his choice for the next 12 months. If the general rules on tariffs should lead to particular hardships for the supplier, or be inadvisable on economic grounds, the supplier can make an application to the Reich Commissioner. This is particularly meant to apply to the transitional period.

The only section in the Rules which does not apply to the final consumer concerns the relations between the supplier of electricity in bulk and the distributing authority. The latter can request their suppliers to alter their existing contracts to the effect that a two-part tariff is to be introduced and that the bulk tariff must enable the distributor to keep within the unit prices prescribed by the Rules. The Reich Commissioner decides in cases where a voluntary agreement between the two parties cannot be reached.

The general impression is that the unifying tendency has not been exaggerated by the New Rules. While the external shape of tariffs all over Germany will be very similar, the actual cost of electricity to the customers of various electricity supply undertakings may differ rather widely. Such a condition is not contrary to the intentions of the legislator. His principal aim seems to have been to make prices comparable, and by such comparison to come eventually to a general lowering and similarity of prices. On the other hand, the Reich Commissioner, whose consent is necessary for all tariffs under the New Rules, can speed up the process of equalization as much as he likes, and upon his decisions will depend how soon a condition approaching uniformity will prevail in Germany. It is too early as yet to say what he is likely to do.

It is interesting to compare the direction of the German legislation with that of authoritative British thought in this matter, and notably with the conclusions of the 1930 Committee and of the McGowan Committee. The findings of the two committees agree with the German Rules in that all supply undertakings should give to domestic users and commercial consumers the option between a two-part and a flat-rate tariff, but there is much less agreement on the basis of assessment for the fixed charge. In the case of domestic users the Germans have chosen the number of rooms; the 1930 Report specifies floor area, while the McGowan Report leaves the decision open; and actual practice in Great Britain seems to favour rateable value at least as much as other bases. (Details of the present position in regard to domestic consumption in Great Britain are given in Table 1.) For business premises, i.e. shops and offices, the German Rules admit floor area equally with demand; the 1930 Report decides for demand only (either measured or on installed lighting wattage), and the McGowan Report, in accordance with widespread practice, definitely votes for the latter. In the case of industrial power the actual practice in Great Britain seems to coincide rather with the German Rules, while the 1930 Report suggests a sort of block system. As regards the unit charge in two-part tariffs, British ideas and German Rules are unanimous in postulating that this charge should be identical over the whole range of two-part tariffs. British practice, on the other hand, has led, and is leading, to much lower figures for the unit charge than prevail in Germany.

FEATURES OF CURRENT BERLIN TARIFFS

Although the figures for Berlin under the New Rules are not yet known, similar existing tariffs of "Bewag" may serve as an indication of future development.

A tariff with a running charge of 8 pfennig (Pf.) a unit is already in operation, if only for highly electrified households. The fixed charges with this tariff are as follows:—

Flat with rooms	1	2	3	4	5	6	7	8	9	For each further room
Fixed charge per month, Marks	2	2·50	3·50	5	7	9·50	12·50	15·50	18·50	2

The normal tariff at present has a running charge of 20 Pf. per unit. It may be expected that this charge will be reduced to the regulation 15 Pf. with or without a slight increase of the fixed charges now in force for these tariffs, which are as follows:—

Flat with rooms	1	2	3	4	5	6	7	8	9	For each further room
Fixed charge per month, Marks	0·80	1	1·50	2·30	3·10	3·90	4·80	6·05	7·30	1·25

Examples based on consumption in typical well-electrified homes of wage-earning classes are shown in Table 2.

On the other hand, in the house of a family with higher spending power (9 assessable rooms) yearly expenditure may vary between £41 2s. (£70 16s. on the new parity) and £65 (£112) with the low running charge, and £51 (£87) and £89 (£153) with the high running charge (water-heating in all cases at 4 Pf. per unit).

Table 2

(A) Tariff with High Fixed Charge and 8 pfennig per kWh

Assume 3–4 assessable rooms.

(1) *Three rooms, and consumption as in British example* (*Table* 1).

	Min. Marks		Max. Marks
Fixed charge:—			
3.50 Marks × 12 months	42		42
Running charges:—			
Lighting, 150 kWh ..	12	(200 kWh)	16
Iron, 50	4	(75 kWh)	6
Kettle and cooker, 800 ..	64	(1 000 kWh)	80
Wash boiler, 200	16	(250 kWh)	20
Water-heating, 1 750 at 4 Pf.	70	(2 750 kWh)	110
Fires, 250 at 8 Pf. ..	20	(400 kWh)	32
	228		306

These amounts are equivalent to £11 8s. (4s. 5d. per week) and £15 6s. (5s. 11d. per week) on old parity, and £19 12s. and £26 8s. on new parity.

(2) *Four rooms, same consumption as in A.*

Fixed charge 5 M. instead of 3.50 M. gives increased fixed charge of 18 M. per annum, so that the above figures would be increased by about £1 (old parity) or £1 10s. (new parity).

(B) Tariff with Low Fixed Charge and 15 pfennigs per kWh

	Min. Marks		Max. Marks
Three rooms.			
Fixed charge	18		18
Running charges:—			
Lighting, 150 at 15 Pf.	22.50	(200 kWh)	30
Iron, 50 at 15 Pf. ..	7.50	(75 kWh)	11.25
Kettle and cooker, 800	120	(1 000 kWh)	150
Wash boiler, 200 ..	30	(250 kWh)	37.50
Water heating, 1 750 at 4 Pf.	70	(2 750 kWh)	110
Fires, 250 at 15 Pf. ..	37.50	(400 kWh)	60
	305.50		416.75

These amounts are equivalent to £15 5s. (5s. 10d. per week) and £20 16s. 9d. (8s. 4d. per week) on old parity, and £26 6s. and £36 on new parity.

In the case of 4-room accommodation, the fixed charge would increase by about 10s. (old parity) and 16s. (new parity) to be added to the sum total.

It will be observed that Tariff (A) becomes more economical than Tariff (B) at consumptions above 340 units per annum.

In considering these necessarily approximate figures, the truest comparison is obtained by using the old parity value (20 M. = £1), rather than the new parity value ($11\frac{1}{2}$ M. = £1).

It must also be noted that the German wage-level is somewhat lower than the British and that in winter the country is distinctly colder, the latter condition being naturally a great obstacle to the introduction of electric heating and cooking.

GERMAN PRACTICE IN RESPECT OF THE HIRE-PURCHASE OF APPLIANCES

Most of the German supply authorities give active assistance in the acquisition of domestic apparatus and wiring on the hire-purchase system. As the trend in Germany is definitely against the selling of apparatus by undertakings, a short description of the Bewag system as inaugurated at the Berlin Electricity Works by one of the authors as early as 1927 may serve as a typical example.

The system, which is called "Electrissima (E^3)," is based on complete abstention from trading on Bewag's own account and consequently on assistance to dealers and contractors only, the E^3 offer being open to all members of the respective associations who have been in business for 6 months or more. The working of the system is best explained by taking an imaginary case.

If a customer approaches a contractor who is a member of the E^3 system, the contractor rings up the E^3 department of Bewag, putting the name of the customer and the proposed deal before them. The Bewag employee in charge then ascertains whether the customer is on the Bewag lines and rings up the Schufa organization (cf. later) to find out whether the customer can safely be given the credit in question. He then rings back the contractor, who has kept his customer waiting, as the total procedure takes only a few minutes. If the credit is agreed the customer signs the hire-purchase contract and can then be supplied with the appliance in question. The contractor sends the contract to Bewag and is paid the cash price for the appliance, less a small cash discount for Bewag and another amount of the order of 20 % covering the part of the credit risk which the contractor has undertaken to bear on his own account. The contract, which enumerates the single instalments, is then passed to the Bewag general accountancy department and the instalments are worked into the consumer's monthly bill. In the hire-purchase contract the consumer consents to having the current cut off in case of default on the hire-purchase instalments, as well as on default on the bill for energy consumed. In consequence hire-purchase losses have always been kept well below 1 %. The increase of the ordinary cash price in these hire-purchase contracts is computed so as just to cover the interest expenses of Bewag, the running expenses of the system being paid out of the cash discount.

The E^3 organization rapidly became popular in Berlin and has contributed considerably to the installation of domestic electric appliances.

The Schufa organization is a sort of co-operative reference organization covering all persons who ever made a purchase under the hire-purchase scheme. The scheme originated with the Bewag when starting the E^3 organization; in a very short time the co-operation of practically everyone who did business on an instalment plan was secured. This made the references very reliable and comprehensive and at the same time, owing to the co-operative spirit of the dealers concerned, very inexpensive. As a matter of fact, taking a reference on a customer costs about 4d., plus the cost of a telephone call.

There is at present a movement towards the standardization of domestic electrical appliances, with a view to reducing the number of types in use and thereby substantially lowering prices. A Government Regulation may be expected soon.

COLLECTION IN GERMANY

In general the German practice is to collect monthly, owing to the fact that a quarterly bill is thought to be too much of a strain on the purse of the great majority of consumers. Prepayment meters are definitely not popular in Germany, partly on account of their cost, partly because of the risk of pilfering, and partly because in pre-War times technical difficulties were experienced. This makes the monthly collecting system a necessity. There are two principal systems of collection. One is to have the meter reading done by workmen, the invoices being written up in the office and a separate gang of better-paid employees being sent out for collecting. The other method is to have the invoices prepared in the office and to hand them out to a better class of employee who does the meter-reading and completes the invoices on the spot in one operation. Experience has shown in this latter case that a trained employee can comfortably deal with well over a hundred customers a day.

The advantages and disadvantages of these two methods more or less balance out. The principal advantage over British practice is that bad debts are kept under one per 1 000, but the cost of both systems is obviously much higher than any possible gain on the head of bad debts. The British system of sending out quarterly bills is less expensive but is probably offset by the need in Britain to use prepayment meters, with their higher capital and maintenance cost, for certain classes of consumers.

All the above remarks apply to low-voltage consumers, large customers being invoiced in the usual way.

CONTRIBUTION TO RATES IN GERMANY

All German supply authorities (companies, municipal authorities, or State undertakings) have now to pay the current and rather heavy local rates and taxes (ground tax and trade tax, the latter being a sort of fixed tax on hypothetical industrial income, irrespective of actual profits). In addition to this all undertakings in public hands are expected to yield net profits more or less on the lines of a private undertaking after meeting debt redemption and rather heavy reserves for depreciation and renewals. These profits from their own works (gas, electricity, and so on) constitute a considerable part of the public revenue of the municipalities concerned. It remains to be seen how the new tariff decrees will affect this source of municipal revenue.

The only other tax on electricity sales is the general turnover tax of 2 %.

TARIFFS IN FRANCE

At almost the same time as in Germany a certain degree of unification has been imposed on the French electrical supply industry.

A decree of the President of the Republic dated the 17th June, 1938, outlined further decrees to be issued in regard to cooking tariffs, off-peak tariffs, and block tariffs for domestic users.

Subsequently a decree published on the 18th August, 1938, obliges all suppliers to offer to their customers on or before the 1st January, 1939, the option of a tariff for cooking and related purposes, provided that the customers subscribe to such a tariff for 3 years and reach a fixed yearly consumption (total and per kW installed). The cooking installation is to be separately metered. The decree lays down certain maximum unit prices, varying from 20 to 50 centimes ($\frac{1}{4}$d. to $\frac{5}{8}$d.) according to geographical situation and the importance of the towns and the villages concerned. Suppliers are strongly encouraged to keep their prices well below that maximum.

Under similar conditions an off-peak tariff is to be offered to users for at least 3 350 hours per year or 8 hours per day. The unit prices vary between 20 and 60 centimes ($\frac{1}{4}$d. to $\frac{3}{4}$d.). The demand under this tariff must not exceed 5 kW.

In the matter of domestic tariffs the French have decided against a two-part tariff and in favour of a three (or more) step or block tariff, the number of units to be included in each step—with the exception of the last—being made dependent on the number of rooms, the area of the flat, or on such other factors as may be arranged between the supplier and the local administrative authorities. A Circular of the Ministry of Public Works points out in this respect that any existing two-part tariffs need not be altered but that, in general, the kind of block tariff adopted by the decree is shown by experience to be much more welcome in France than the two-part tariff. It goes without saying that only one meter is to be used for all blocks.

The range of customers to whom the block tariff must be offered includes both domestic and agricultural users, up to a maximum of 5 kW and down to a minimum of 1 kW per installation. A 2 years' contract must be entered into for this tariff.

The rules governing the block tariff are much more complicated than the German ones and are chiefly of local interest only.

The first block of units is to be offered at the normal price for lighting. The units of the second block, half the number in the first, must not cost more than 75 % of the first block, with a minimum of 1 franc ($1\frac{1}{4}$d.). The cheapest block is to be offered at the cooking tariff price as set out above. In any event, the suppliers are authorized to charge for 40 kWh a year on the first block.

The French rules are much more generous than the German ones in assessing secondary rooms; kitchen, passages, bathrooms, lavatories, cupboards, cellars,

attics, and garages, count altogether as one room. In rural conditions living rooms are assessed as $\frac{2}{3}$, and stables and barns as $\frac{1}{4}$, quite independently of surface.

The Circular gives examples to show in what manner the number of rooms determines the number of units for the first block. First place is given to the Paris tariff, where the first block is 60, 90, 120, 160, 200, and 240 units for 1, 2, 3, 4, 5, and 6 rooms respectively.

Apparently the authors of this tariff scheme expect a rapid promotion of electricity sales through it; this is the only explanation that can be given for the fact that no supplier must accept a new customer under this tariff if the investment connected with the customer exceeds the not very high figure of 150 francs (approximately 15s. 7d.).

As under the German regulations, bulk suppliers are obliged to consent to such alterations of their selling price as make it possible for the distributor to keep within the imposed price-limits.

In one direction the tendency to unification goes rather beyond anything so far decreed or even suggested elsewhere. Within a *Département* (county) a majority of communities can impose on all its communities a uniform tariff.

The German New Rules are an attempt to establish a compulsory framework for electricity tariffs to be applied to the whole of a big country. Comparison with other countries shows that these Rules are in accordance with the general opinion as to the right form of electricity tariffs, and the detailed description seems to prove that the Rules are sufficiently flexible to meet the varied requirements that must naturally occur in any country with a complex economic system, both industrially and agriculturally. Although they do not present many new concepts the German Rules are logical and at the same time practical, and when handled in a liberal spirit by the Reich Commissioner will produce results helpful to those considering the matter in other industrial countries.

The trend of the French regulations is not very different from that of the German ones, though owing to the fact that they are part and parcel of a legislation concerned with all aspects of French economics they do not so much touch fundamental matters, but are satisfied with adding details here and there.

Another reason for the less comprehensive character of the French rules is that in France, as distinct from Great Britain and Germany, the bulk of electrical supply is in the hands of companies (not the municipalities or the State); there is also the ingrained French respect for property interests.

CURRENT BRITISH TENDENCIES AFFECTING TARIFFS

The rights and liabilities of the statutory undertakers under the Electric Lighting Acts and Orders in regard to charges are briefly as follows:—

They must not:

Charge beyond a maximum price as stated in their Act or Order or as subsequently revised by the Electricity Commissioners.

(Revision may arise at 3-year intervals on representations made by the local authority, when not the undertaker, or by not less than 20 consumers.

In the case of power and some other companies, there is a further provision for the dividends to be subject to variation from a defined standard in relation to the average price obtained by the company in the year, reduction in average price permitting increase in dividend, and vice versa.

Such sliding-scale relation between prices and dividends may be imposed by the Commissioners on any companies when they take a supply from the Central Board.

No discrimination in charges may be made between consumers who offer like conditions of supply.)

They may:

Subject to approval of the Commissioners, offer tariffs exclusively of the "all in" type, but alternative flat rates are usual.

Make a defined minimum annual charge.

Make charges or impose minimum payments in relation to capital cost of supplies requiring special works and which are beyond the scope of their general distributing system.

They are permitted and recommended to:

Offer tariffs of the "all in" type.

Provide wiring and appliances on hire or hire purchase, establish showrooms, demonstrate the use of electricity, offer a comprehensive "consumer service," and contribute to approved associations promoting these objects.

Within these limitations they are at liberty to fix charges or enter into special arrangements with consumers; and supplies of a character or magnitude involving high-voltage connections and/or substantial outlay are usually the subject of agreements maintaining special prices and conditions for a term of years.

Value of Electricity to the User

Electricity offers to the user a form of energy more adaptable to his needs than any other, but one which varies widely in money value to him in accordance with the use to which he puts it.

It follows that the supplier cannot to any great extent base his charges upon what the traffic will bear. In making a tariff to meet those purposes which can be more or less well effected with a competing medium he must often provide energy for other purposes at a price lower than the user would pay if it were possible to have price differentiation according to the object of the supply.

From these considerations and the circumstance of the supplier, enjoying a quasi-monopoly in perpetuity, it arises that the cost of supply has become the basis of charges for supply. Out of this, and from the desire to make the tariffs "load building" in character, has arisen the interest in the subject and the immense variety of forms of tariff, tending now, however, at least in regard to low-voltage supplies, towards a greater uniformity and simplification as supply engineers regard

their costs more and more in relation to consumer groups than to individual cases.

At the present stage in the technique of generation marked reductions in costs, fixed or running, are not anticipated. It appears, therefore, that one must look to wider applications to bring about any notable reduction in cost at the consumers' terminals, and for justification of the large investment in consumers' apparatus to which the industry is committed, at least for domestic supplies.

Expenditure on generating and distributing plant is continuous and, being principally dictated by growth of the business, it follows that standard rates can be applied to the majority of consumers, including in most cases quite considerable users of power from the general network, without special provisions in regard to payments or period of contract. To this extent standardization of tariffs is desirable and indeed necessary owing to the readiness with which users in some classes can compare the terms under which they buy, a tendency increased by the amalgamation or grouping of trade and manufacturing interests so common to-day.

When catering for very large users in any class, however, frequently needing high-voltage supplies, involving heavy expenditure useful for no other purpose, and perhaps associated with on- or off-peak features affecting the marginal cost of the particular supplies, complete freedom of action is necessary in order to meet the competition of private plant and give security for a reasonable period to the undertaker and to the main body of his consumers, who should at least have the prospect of ultimate advantage from any substantial increase in the undertaker's business and responsibilities.

The conditions of such special supplies vary very much, as does also the "value" or relative importance of power cost to the prospective user, and so far as is consistent with treating like conditions in a like manner the supplier should be in a position to charge what the traffic will bear.

Although for large industrial supplies charges on measured demand and unit consumption are the most scientific, there is to-day a greater readiness to meet the objections to this system often expressed by the power buyer by substituting block or discount rates. As industrial establishments specialize more narrowly it becomes apparent that they each offer to suppliers load factors peculiar to their business and not susceptible of alteration by any ordinary variation in charge for electricity.

So extensive is the use of public power supply that most new business now arises in connection with newly established industries, and frequently their establishment gives rise to the local housing of numerous employees, who may, under suitable conditions, collectively use as much electricity in their homes as do the works where they are employed.

Standardized Tariff Forms

It would appear that the imposition of certain forms of tariff as compulsory upon all undertakers for particular classes of supply must relate to the national fuel and power policy, even if that is not expressed in legislation but only develops out of competitive conditions and technical advancement.

If, for example, in any community it is implied that major heating in the home is to be left to gas and improved usage of raw fuel, leaving to electricity the lighting, labour-saving, and subsidiary or convenience applications of heat, it becomes easier to standardize a tariff for a long period ahead.

On the other hand, so long as there is a desire, mutual to suppliers and consumers, to work towards entire dependence upon electricity for every purpose in home use, one must have regard to the magnitude and unknown quantities of that problem. It is already obvious in this country that in a few years the domestic demand may dominate the supply situation. In spite of diversity in times of use and altered home habits, the period of maximum demand on generators and mains may change its position in the 24 hours and also become much longer, giving to all undertakers a load curve similar in form to that of the purely industrial districts to-day. In that event, and with houses averaging 5 to 15 thousand units per annum (say $1\frac{1}{2}$ to $4\frac{1}{2}$ thousand per head), the basis of the fixed charges imposed at present may become less sound, perhaps even undesirable, and it may be advantageous to substitute annual minima or a secured revenue against overhead costs collected rather in the form of a guarantee to use regularly certain appliances and methods in the home.

The influence of "all in" tariffs with a simple fixed-charge basis has been so beneficial in domestic electrification, and is still so important a factor in developing this class of supply, that it is easy to regard them as a permanent feature, but it must be remembered that even the most favourable of such tariffs now in use are in the nature of compromises between cost division and consumer reaction. Fixed charges have to be kept as low as possible because the electrification of the home is essentially a progressive business. There is seldom the possibility of selling from the start that complete use which would support a very high fixed charge and very low running rate; therefore the unit charge is made as high as competition dictates and in itself bears some portion of the fixed costs, with, however, the disadvantage that such contribution varies with the quantity used rather than the rate of demand. When, however, a very high average use of electricity is reached in some millions of homes it may well be found that a simple form of block tariff with a minimum payment will meet most needs.

D. J. Bolton, in his book on "Electrical Engineering Economics," says—"If in a two-part tariff there is correct division between fixed and running charges in relation to costs, the former become so high as to penalize the poor-load-factor consumers, who offer a greater probability of diversity than the high ones, hence the practice in most domestic tariffs of keeping the fixed charge down and the running charge up in relation to true cost division."

In considering forms of domestic tariff which may become more or less permanent, it is necessary to consider not only the trend of electrical application but changes in the layout of dwellings.

The mechanization of the kitchen, for example, tends

to restrict its use to the performance of kitchen tasks, making it less occupied by the small householder—or the maid, in more spacious homes—than in the past. Similarly there is a tendency to provide, notably in flats, larger living rooms with alcoves or recesses for meals, providing a relatively large room in less space than would be occupied by two of smaller size, so giving more convenience and useful occupation of floor space. Such changes may make a floor-area basis of charging more representative of electrical demand than a per-room basis. Some undertakings who state the annual fixed charge on a house without declaring its relation to size or other features are believed to take into their calculation both the rateable value and the size of the premises, so bringing into the fixed annual payment consideration for area normally occupied, lighted, and warmed, and also the status of the dwelling in regard to position, occupier's income, etc.

Leading Methods of Establishing Fixed Charges

Rateable value.

Rateable value, one of the earliest systems, is in very extensive use and is giving good results.

Obviously it has the defect that the rateable value of dwellings is fixed by a non-electrical authority. It might be raised, when there could be opposition to raising the electricity fixed charge; while on the other hand it might be lowered, when calls for a reduction in the electricity charge would certainly arise.

Assessment practice varies as between town and town, some tending rather to low assessment and a higher rate in the £, others to keep the assessment up for the benefit of lower poundage. These conditions are sufficiently well met by the varying percentages on the assessment used in different supply areas.

Within a particular town, assessment does not quite follow the size of house or very closely indicate electrical needs. It may be on a higher level in the richer quarters or those possessing some situation amenity, and to that extent the electrical charge may be a little heavier on the well-to-do classes. It should not be heavier to such an extent as to check business with them, but it constitutes an action in the reverse direction to that applying to gas and raw fuel; gas charges being uniform, perhaps a little higher to the poorer users where prepayment meters are employed, and coal tending to cost more to the small buyer. On account, however, of the considerable uniformity as regards the relation between the size and accommodation of most houses and their rating assessment, this system has been very successful in practice over a long period of years.

Floor area.

This method is in extensive use. It has the merit of relating the charge to lighting demand. Although details vary widely (inside measurement, outside measurement, exclusive of parts of the house where use of electricity is intermittent, etc.) it is understood by the consumer, fixing of the charge calls for but little inquiry, and extension of use is free of restrictions.

Number of rooms.

This method is gaining in favour, again on the score of simplicity, and ease of determination and check. Occasional departure from normal areas is, in some tariffs, provided for by a limit in the area to be counted as one room; there are also exclusions, as in the floor-area system.

Some undertakings place less dependence on average results, and compute fixed charges with reference to both area and rateable value, or estimate for different classes of property the demand of normal lighting. These methods may give a more accurate result in regard to individual consumers but have the demerit that the charge has to be put forward without declaration of the basis upon which it is framed—so inviting argument, because it appears to the consumer to be arbitrary and irrational compared with a known flat rate per unit consumed.

Charges based upon lamp wattage, lighting points, and features of the installation, tend to fall into disuse as they obviously call for periodic check, and restrict extension and the more modern installation methods which encourage the multiplication of points and outlets to the benefit of supplier and user.

The difficulty of the tariff maker lies in the fact that he must collect his costs and a profit under existing conditions of supply and yet offer the strongest inducement for those conditions to be improved.

Exact particulars of the division of domestic supplies between the different forms of "all in" tariff are not available, but a review for 1937 gave 233 undertakings (37·5 % of total), covering about 36 % of the population, as offering the rateable-value form of tariff.

In "Costs and Tariffs for Electricity Supply," by D. J. Bolton (1938), the "all in" tariff position is given as follows:—

Out of 171 undertakings with annual output above 10 million units, 154 (90 %) offered all-in tariffs, the types being in the following proportions:

Rateable value	47 %
Floor area	21 %
Room basis	10 %
Maximum demand	8 %
Other bases	14 %
	100 %

Promotional Value of Tariff Forms

The inherent advertising value of a simple method of charge is often lost by the manner in which its justification is explained to the consumer.

The "all-in" tariff for domestic supplies has now become so general that the early difficulty of diverting consumers to it from flat rates per unit is apt to be forgotten. There is evidence, however, that the transition would have been more easy and increased consumption more rapid but for the technical accuracy and bad salesmanship with which its advantages to the user were described—usually as a lowering of the average cost of the unit with increase in consumption. The result was that it seemed to the user that the unit never reached a figure at which it could compete for cooking or water-heating, whilst he failed to appreciate that it

quickly fell below the price he expected and was willing to pay for lighting.

In all successful two-part domestic tariffs the fixed charge disposes once for all of the great increase in the cost of generating a unit which arises from the small annual consumption of units per kilowatt of demand associated with lighting during the dark hours of the day; and, having disposed of that item at a figure which is not unreasonable for the lighting service, it leaves open to the consumer an unlimited supply for other purposes at some low figure fully competitive with local alternatives.

Electricity Charges Easily Adjustable

For commodities sold for cash across the counter, prices conveniently related to the coinage are essential.

An increase in the price of sugar by 10 % from 3d. to $3\frac{3}{10}$d. per lb. presents difficulty, 7 lb. for 1s. 11d. probably being the solution. Again, the vendor of a packet of cigarettes at 6d. must himself bear minor changes in cost, or would have to meet competition by increasing the number or weight of the cigarettes. "Competition within the coin" is the economist's phrase for this. With electricity, however, the problem of passing on small variations in favour of or against the buyer is so simple that the general adherence to coinage denominations is surprising, as energy can so readily be sold by the shillingsworth for different numbers of units, allowing fine variations in the actual rate paid for the legal unit of energy.

Unlimited Supply

The suggestion has sometimes been made that electricity could be supplied to the home without limit for an inclusive annual fixed charge, presumably related to installed capacity and perhaps associated with peak restriction and storage methods, the parallel of water supply being cited in support.

It would not appear, however, that such a method could be justified on either national or consumer economic grounds. Under complete freedom from restriction individual peak demands might well equal the installed capacity (always difficult to ascertain) and in severe winters constitute the major part of the system peak. Under such a method of charging the careful user would yield the most profit to the supplier, while the careless one, paying no more, would be free to squander heat (i.e. coal) by opening windows rather than turning switches.

A solution may perhaps be found in charging by the kilowatt-year, as is the practice in some countries largely dependent upon water power, although such methods are usually associated with peak restriction and extensive use of heat-storage appliances.

Domestic Load

This extensive consumer group is the only one in which suppliers, strictly speaking, sell retail, supplying the ultimate user. In other forms of supply the charges become an item in the cost of some commodity or service provided or rendered to others by the consumer. So it is in the domestic supply that one has the final test of money and amenity value in comparison with other methods available to the user.

So much does the extension of electrical methods in the home depend upon the appliances used, and their cost, performance, and upkeep, that it is not possible fully to consider the domestic-supply tariff problem apart from the consuming appliances and their cost.

The rate at which homes are being electrified proves that appliances are now efficient and reliable and that supply and service are being sold on a price level which satisfies the user and induces him steadily to pass to the supplier money which he has been in the habit of spending on coal and gas.

The growth of the domestic electric cooker may be taken as an index of the movement and is represented by the following figures (for all types of cooker). These are based on several returns and are probably within a small percentage of accuracy, particularly in the later years.

	1934	1935	1936	1937
Numbers	490 000	676 000	876 000	1 103 000
Ratio ..	100	138	179	225

The 1937 total gives a purely arithmetical average of 129 cookers per 1 000 consumers, but in the highly developed areas figures of 300 to 500 have been attained.

Provision of Appliances

The consumer's overall expenditure comprises both the supply and the consuming appliances, and experience has shown that the time has not yet come when low rates for energy alone will create an extensive domestic business.

In most of the supply areas in this country where domestic development has been notable, the undertaker has invested large sums on the consumer's side of the meter, offering all the high-consumption appliances on simple hire with maintenance and tending more and more to express the hire charges in the simplest form of pence per week. Extension of these methods to the more expensive and permanently fitted forms of electric heating appliance may go far to secure an "all winter" heating load and overcome the difficulty arising from the cheaper forms of radiant heater used excessively for short periods as a supplement to fuel.

Need for Statistics

It would be helpful if undertakers could make a more detailed separation of domestic from general low-voltage returns. Many figures are available but it is to be feared that they are mostly raw averages taken without particular care to exclude extremes and to that extent not a reliable guide to the conditions likely to arise in a few years, even at the present rate of progress.

Where a supplier has homogenous groups of consumers equipped with apparatus on hire or hire-purchase, and their income restricts the acquisition of other electric appliances, fairly accurate values can be obtained of

installed capacity, consumption, maximum demand (extent and time), and diversity computed therefrom; but where (as in most cases) the supplier has not that extensive interest in the user's installation, and has no distributing centre exclusive to a particular class of user, it is very difficult even to approximate to these values, the knowledge of which would be so valuable, particularly as regards their trend following extended use of electricity in the home.

Any form of census-taking is objectionable and likely to defeat its own ends, whilst exploration by recording instruments is an expensive matter, and undesirable on the consumer's premises. One has therefore to be content with feeder readings of kilowatts, kilowatt-hours, and time, taken in substations. These can be associated with a list of all premises connected to the particular feeders, and the remainder of the information so much needed, namely details concerning the consumers' apparatus and its use, can to a notable extent be obtained by a well-trained selling staff, in the course of offering further facilities to the user. By this means it is possible to discover fairly closely what appliances, of which the supplier has no record, exist, and how they are used. Such an inquiry need only be made within well-chosen sample groups, and the results obtained from it may be expected to be representative of practice throughout the area.

A sales staff (carefully directed) might give valuable help in such an investigation without the user becoming aware of anything more than an effort to sell extended service.

It is not suggested that such an effort would be cheap or should be undertaken without care and special training of the operators, but it is suggested that the connection between the vast load now rapidly being built up in the home and the usually very simple tariff of the £x-per-annum-plus-yd.-per-unit class requires to be established (not for individual cases, but for groups) in a far more scientific way than has yet been done.

THE HEATING LOAD

The period of unusually cold weather at the end of 1938 revealed a great deal of submerged load due largely to the use of heating appliances, but also reinforced by extra cooking and the failure of some alternative water-heating devices.

To meet such demands, even if infrequent, entails cost to the distributor in the provision of plant or the demand charges on bulk supplies, although in the latter case the undertaker may only have to pay for excess demand in the years when it occurrs. In all cases, however, one is apt to give too much consideration to the high cost of meeting exceptional loads and too little to the real solution, which is to bring about so general a use of the appliances throughout the year that the revenue derived from them will support occasional abnormalities and make it as unnecessary as it is undesirable to check the consumer in the fullest employment of a service whose advantages have been so persistently advertised.

Even the radiant electric fire, far as it is from offering the ultimate method of applying electric heat, need not be feared if it is supported by an ample background of cooking and water-heating consumption.

Application of Heat

Although beyond the scope of this paper, one may be forgiven for referring to the need for research in methods of applying electricity to the heating of buildings and their occupants.

In all the other applications of electricity the main problem has been solved. Technical development is continuous in both breadth and depth, the apparatus in general use gives satisfaction, and its employment is in most areas competitive in cost.

For indoor artificial heating, however, electricity has provided a vast range of appliances of luxury and convenience, only too easy to use as a stand-by or a supplement to competing methods which, far less convenient to the user, allow their supplier the benefits of storage, i.e. relieve him to a great extent of those peak-demand cares which trouble the provider of electricity, not on account of the peak produced but because it is inadequately supported by revenue from regular use during the greater part of the year when artificial heat is needed. In short, because electric heating is still too much of a stand-by or supplement, a condition encouraged by the cheapness and simplicity of the ordinary radiant fire, the remedy is not in restricting this habit-producing application which gives so much satisfaction to the user, but in the evolution of improved ways of applying electricity to the heating of buildings, and making it, as is the case with lighting, an element in the design and layout of the house. In this direction research seems to be far in advance of practice, and the time may have arrived for supply engineers to offer the public hire facilities for more extensive and permanent heating equipment, with skilled advice on its adaptation to the various needs of the home.

At a recent International Advertising Convention, Mr. W. Howlett put forward the following figures relating to the country's domestic purchasing power:—

Families in Britain	11·75 million (approx.)
Divided into:—	
Well-to-do (liberal purchasers for cash)	0·6 million
Medium (good standard of comfort, apt to need hire-purchase facilities) ..	2·6 million
General wage-earning (small purchasing power beyond essentials)	8·6 million

This analysis suggests to the suppliers of electricity the possibility of a vast public service, a great influence on the conditions of life, and no little responsibility.

APPENDIX

Extracts from Decree by the German Government on Tariff Forms for the Supply of Electrical Energy to the Ordinary Consumer, 25th July, 1938

Para. 1.

Suppliers are obliged to make general tariffs for domestic, commercial lighting, and power and rural consumers.

Para. 2.

1. The standard form for general charges is the all-in (two-part) tariff.

2. This tariff consists of fixed and running charges; the two together must include the payment for electricity supplied and all costs connected with supply, particularly for metering, billing, and collecting.

3. The fixed charge has to be assessed on a yearly basis and independently of current consumed in accordance with paragraphs 5 to 8. It must be collected in instalments.

Para. 3.

The following are admitted as bases of assessment for the fixed charge: power installed; power demanded; power contracted for (all measured in kW or kVA) so far as the provisions of paragraphs 5, 6, and 7, do not admit other bases.

Para. 5.

1. For domestic supply, the basis of assessment is the number of rooms and not the installed capacity.

2. Each habitable room and one kitchen per household may be assessed as a room, irrespective of whether or not there is an electrical installation in it.

3. The following do not count as rooms:

(*a*) Rooms of less than 6 m^2

(*b*) Corridors, lounges, open balconies, bathrooms, lavatories, cellars and attics, sculleries, storage and similar rooms.

(*c*) Garages for private use; such rooms as are used for agricultural purposes (apart from farm buildings proper).

Where single rooms in dwellings are used for trade or professional purposes, the fixed charge can be assessed according to paragraph 6.

Para. 6.

1. For commercial and professional demand, room area can be taken as a basis of assessment, instead of power installed. It is also admissible to offer the two bases alternatively or interdependently.

2. If area is used as a basis of assessment, rooms have to be divided into classes, for which the total area has to be taken as a basis of assessment.

Para. 7.

1. For the total demand of rural consumers, agriculturally used area (in hectares) may be used as a further basis of assessment. If a consumer chooses this basis, it takes the place of the bases in paragraphs 3 and 5.

2. When computing agriculturally used area, forests, water, waste land, heath, mountain, meadows and lanes, etc., must not be included.

Para. 9.

1. All consumers must be offered the option of two tariffs with different fixed charges and running charges, as set out in Section 2. No limitation of use must be imposed.

2. Running charges must not exceed 8 Pf. per kWh in Tariff I and 15 Pf. in Tariff II.

Para. 10.

Suppliers are obliged to offer still another tariff to very small consumers, including those with low utilization. This tariff implies a higher running charge and lower fixed charge, without the restrictions of paragraphs 3, 4, 5, 6, 7, and 9.

(The circular establishes that the fixed charge must only include costs of metering and invoicing.)

Para. 11.

Suppliers must offer to all consumers energy which is to be taken within certain times of the day, at the suppliers' option, at a running charge of 4 Pf. For these tariffs suppliers are entitled to impose restrictions on use and to increase by an appropriate amount the basic prices established on the lines of paragraphs 9 and 10; or they can, on the other hand, impose a minimum payment.

Para. 12.

Suppliers are entitled to charge a lump sum for the consumption by certain appliances within any installation if the consumption by these appliances can be established with sufficient accuracy without measuring.

Para. 13.

1. The consumer is bound for a year to any option he may have exercised between different tariffs.

2. If a consumer does not exercise an option to which he is entitled, the supplier may make the decision in his stead, also for the period of 1 year.

Para. 14.

1. Distributors can ask their bulk suppliers for a new offer based on a yearly fixed charge and a running charge for each unit taken, or some similar tariff. The supplier has to comply with such a demand within 2 months.

2. The offer must take into account the obligations imposed on the distributor by paragraphs 9 and 11. When fixing hours (11) the requirements of the supplier have precedence over those of the distributor.

3. Should the distributor and the supplier not come to an agreement, the decision lies with the Reich Commissioner.

Para. 18.

Offences against this decree are punishable with imprisonment or fines up to an unlimited amount.

[The discussion on this paper will be found on page 581.]

DISCUSSION BEFORE THE INSTITUTION, 30TH MARCH, 1939

Mr. J. M. Kennedy: To anyone who has studied electrical development in this country and has realized the chaotic state of tariffs which has been brought about by the fact that electrical distribution is now in the hands of some 600 separate undertakings, any proposals such as the German decree for standardization of tariffs cannot but be most interesting. I should like to examine the proposals which are included in that decree, to determine how far they meet what we should consider to be the needs of this country.

One of the main advantages of the German decree is that it puts in the forefront of all tariffs for domestic purposes a two-part tariff. We in this country have two-part tariffs, but only for the most part as alternatives to flat rates. In this country the fixed charge is settled on the basis of, for example, the number of rooms, or the rateable value, or the floor area. It does not matter very much what the criterion is, as long as there is the will to standardize. The room or floor-area basis has a great advantage over the rateable-value basis in that it does not produce the anomalies which always arise when premises of the same size, occupied by the same number of people, are differently assessed because of their different location in the town, or because some are in a town and some in a rural area.

As regards the running charge of the two-part tariff, the figures of 8 and 15 Pf. quoted in the paper are somewhat high as compared with the figures, to which we are accustomed now, of $\frac{3}{4}$d. or $\frac{1}{2}$d. a unit, or even 3 units for 1d. Is there any scientific basis for the fixing of those apparently high running charges, or are they due to the fact that the fixed charge is rather on the low side?

On page 571 the authors say: "The flat-rate tariff may also be combined with the two-part tariff in such a way that at the end of each year the consumer is charged either on the original flat rate or on the two-part tariff, whichever is the more favourable to him." This point is very important, but is frequently disregarded in this country. Consumers who are charged on flat rates often gradually increase their consumption without anyone drawing their attention to the fact that if they changed over to a two-part tariff not only would they obtain their present requirements for rather less money, but they could greatly increase their consumption at a very small extra cost.

I notice that the German tariff differentiates between domestic and rural consumers, and I should like to know whether the domestic consumers in rural areas are treated as domestic consumers or as rural consumers. If they are treated as domestic consumers, it would be interesting to know, in view of the statement that the fixed charge includes all costs connected with the supply, whether a domestic consumer in a rural area can obtain his service free of charge and whether any limitation is placed on the length of the service main.

The German decree bases the fixed charge on the area of the agricultural land; what is the rate charged per hectare? The proposal made in that decree is one which would be very acceptable to farmers in this country. It is interesting to note that, in spite of the consideration which has been given to this problem, our colleagues in Germany have not overcome the difficulty of fixing commercial tariffs.

I would draw attention to the lowness and the compulsory nature of the off-peak tariff. The average cost given in the first column of Table 2, namely 228 M. for 3 200 units, works out at 0·86d. per unit; and for the higher consumption quoted in the second column (total cost 306 M. for 4 675 units) the average works out at 0·785d. Those prices appear quite reasonable for a complete all-in supply. Could the price be still further reduced if all-day operations were transferred to the off-peak unit rate of 4 Pf. a unit? Presumably such a change-over would involve time switches, and it would be interesting to know whether they would add appreciably to the cost.

Turning to the figures in relation to French practice, in this country we should be against the proposal to meter cooking and other purposes separately from the general supplies, but the proposed stepped or block tariffs, with the number of units in each of the first two steps depending upon the size of the premises, have much to commend them. Such a tariff is in force to-day, and has been in force for many years, in the Glasgow area, where all premises are assessed and the consumer is told that in respect of his premises so many units will be charged at $3\frac{1}{2}$d., so many at $\frac{3}{4}$d., and all beyond that at $\frac{3}{8}$d. The system has the great advantage that all consumers are automatically on the two-part tariff, whether they want to be or not, and all can obtain the benefit of the very low unit rate if only they will increase their consumption. In Glasgow, which has a very large number of domestic consumers, the average consumption per domestic consumer is nearly 700 units.

With regard to the practice in Great Britain, I should like to correct the authors' statement that the Commissioners are concerned with the revision of maximum prices; that is a function which is reserved to the Minister of Transport. I do not agree that the cost of supply has become the basis of charge. We have, of course, to make both ends meet, but the price charged is more a question of expediency. For example, we know that almost the first use which any domestic consumer makes of electricity is for lighting, and for that supply he will undoubtedly be willing to pay a considerably higher price than for heating or cooking.

In framing our tariffs for dealing with domestic supplies, we must bear in mind that almost 85 % of the population in this country live on incomes of under £250 a year, so that there is no margin for them to spend on luxury. If we want the households to become electric we must supply electricity at a price which will compare with the weekly cost of any alternative. The weekly cost of other methods of lighting, heating, cooking, and so on, was recently investigated by a committee, and it was found that the figures varied from about 4s. to 6s. a week in the smallest working-class households. It is for that figure that we have to supply electricity in order to compete with other methods. We can, I am quite convinced, do that, and when we get our tariffs properly framed throughout the country we

shall achieve a large measure of complete domestic electrification.

Mr. J. W. J. Townley: I was very glad on reading this paper to find that the French and the Germans have not disregarded economic principles in framing their tariff regulations. One great advantage that I see in the German regulations is that although they do not provide for uniformity of charge throughout the country, they do provide for uniformity of tariff structure. The explanation given to a consumer in one town as to how the tariff affects him is precisely the same as the explanation which would be given to him in another town. My experience is that it is not the complication in a tariff itself which is troublesome to the consumer, but the fact that when he discusses it with a friend and wants a point cleared up, he finds that his friend is thinking of something entirely different, because his particular tariff is of a different form. The difficulty with British electricity tariffs is that they vary so much in different parts of the country.

Regarding the authors' plea for simplicity, my own undertaking has had in operation for many years an all-in tariff in which the hire of apparatus is included with the unit charge. It is popular with the small consumer because it is simple to understand. As a result of adopting it I have about 50 000 domestic consumers in a very poor working-class area, and my figure of consumption per domestic consumer is 625 units per annum, compared with 250 units per annum 5–6 years ago.

Under the German regulations considerable discretionary power seems to be left to the supply authority, and unless this is more clearly defined there may be difficulties with the consumer.

On page 571 it is stated that a flat-rate consumer may have his account changed to the two-part tariff where this is more favourable to him. I agree that every possible opportunity should be given to the consumer to change from the one tariff to the other when the change is going to be beneficial to him, but if this is permitted from year to year it will create tremendous confusion and additional cost, which must ultimately be reflected in the charges.

I am surprised to learn that prepayment meters are not popular in Germany, because in this country a particular form of prepayment meter of German origin is very popular indeed. Last year in my area we took 150 tons of money out of our prepayment meters, and I had with me to-day an engineer from a North Country town who told me that of the 40 000 domestic consumers in his undertaking, 30 000 were on prepayment meters.

German municipal undertakings apparently have the power to operate as profit-making undertakings, and the profits are taken over by the municipality for use in meeting local expenses. In this country it is permissible for a certain contribution from the surplus of a municipal undertaking to be applied to the relief of the rates, but the arrangement is not generally accepted as being sound in principle, even by those municipalities which adopt it as of necessity. By allowing a surplus to be used for the development of the undertaking we provide for posterity. Thus in the last 5 years my own undertaking has provided over £250 000 for the purchase of hire appliances, etc., out of its surpluses.

I should like to support the author's plea for more accurate statistics relating to domestic supply. I believe that some steps are being taken to secure such statistics for the Electricity Commissioners, making it possible to separate domestic supply from commercial heating and lighting supplies.

There is one point which the authors make that I support very heartily. They suggest that costs and tariffs should be considered in relation to groups and not to individual consumers. One of our troubles in the past has been due to the fact that we have tried to make each consumer pay his proportionate share of the cost of giving him a supply. That cannot be done with large numbers of small consumers; they have to be dealt with in groups, and tariffs devised so as to secure the best possible returns from each group.

Mr. C. T. Melling: It is interesting to see that in Germany the fixed charge is relatively low and the running charge relatively high. Dealing with English tariffs, the authors say "the unit charge is made as high as competition dictates and in itself bears some portion of the fixed costs." It seems evident that the German authorities have also had that point in mind. To do otherwise, in fact, would not be correct, because each additional unit consumed must bear its full share of both fixed and running costs. If the ratio of fixed charge to running charge in a tariff is the same as the ratio of fixed costs to running costs, then eventually an additional load means an additional loss to the undertaking, instead of an additional gain. It is not possible, therefore, to equate costs and charges on a two-part tariff and expect the result to be a scientific tariff which will work in practice. Most tariffs are based on utility rather than cost, and the cost of the supply indicates not the value of the components of the tariff, but the lowest tariff which can be charged.

There is usually a big variation in the fixed charge on domestic two-part tariffs for houses of different sizes. This would not be so if tariffs were designed on a cost basis, because if the running charge bears its true share of fixed costs and the fixed charge consists of consumer cost plus the cost of the basic lighting of the premises, the fixed charge should be more nearly constant, as the costs of basic lighting, meter reading, accounting, and other consumer services do not vary in proportion to the size of the house. In practice it is usually considered that if the fixed charge varies in proportion to the size of the house the tariff is acceptable, although there are cases where the supply authority increases its fixed charges at a still higher rate.

The three forms of assessment chiefly used in this country—rateable value, number of rooms, and floor area—seem equitable. For one particular house each of the three bases would give a different fixed charge, but very few cases come to light where the consumer wishes that he were charged on another basis, because, in most cases, consumers do not know what the fixed charge would be in another area. If legislation required a standard tariff structure for domestic premises there would be reductions in some fixed charges and increases in others owing to the poor correlation between the various bases.

It is interesting to note that in Germany the small consumer is allowed to have a flat rate and is given special consideration. There is a danger that too much consideration may be given to the small consumer Such

consumers may be of very poor purchasing capacity, and an undertaking runs considerable danger in connecting too many of them at the very low charges offered by some undertakings. For example, a case was recently examined in an industrial town, where out of 10 000 consumers 50 % were on the prepayment rate; 20 % of all the consumers in the town paid less than £2 a year, while 10 % paid less than £1. Those who paid less than £1 a year were clearly uneconomic consumers, and those who paid less than £2 a year were not profitable. In that town a serious condition may arise when slum clearance schemes are adopted involving the demolition of thousands of houses. It is frequently found that a slum clearance scheme, under which consumers have to move into new houses where the rents are higher, means that the people have relatively less purchasing capacity for the other necessaries, and therefore the 4s. or 5s. which they normally expend on solid fuel, electricity, and gas, must be reduced, just as their food bill is reduced. This means that these uneconomic consumers tend to become less economic still. Propaganda should be employed to make such people better consumers, instead of reducing the tariff to its very lowest limit.

The authors' remarks on the effect of the recent cold spell are welcome, as many undertakings have incurred heavy losses through the development of the fire load. In a sample area, tests were made which show that in 1938 the cost of supply on the C.E.B. tariff for the fire load was more than 2d. per unit, and in this case the grid tariff was clearly inequitable. It is hoped that a modification will be made in the method of charging adopted by the Central Electricity Board.

With reference to the possibility of legislation in this country to standardize tariff structure or tariff charges, a first step would be to prevent the formation of new tariff areas. Many local authorities in this country have the option to purchase the local company undertakings, and if the disintegration of supply areas is allowed the future will see many additions to the present multiplicity of tariffs.

Mr. W. Fennell: In the matter of standard forms of tariff other countries have acted while we have been talking. It is three years since I pointed out, in the discussion on two papers on tariffs,* that the time had almost come when the Commissioners, who alone could do it, should implement their opinion and decide on a standard two-part tariff system, and insist upon its adoption by a certain date; adjusting the prices to bring in approximately the same total income as from the existing two-part tariffs. Then, having the authority of the Commissioners, the supply undertakings would be able to refer the consumers who complained of the change, who would be those who had to pay more, to the Electricity Commissioners, who are experienced in dealing with complaints, and the desired object would be attained.

With regard to the German alternative two-part tariffs, I imagine that the high unit charge of the alternative was really intended to deal with the purely lighting consumer, and to give him a reasonable reduction if he is a long-hour consumer. This suggests that there is another factor to be taken into consideration which has not been referred to. I think it probable that the municipalities in Germany generally own the gas undertakings as well as the electricity undertakings, and wish to reserve the heating load for gas as far as they can reasonably do so. I should like to know whether my assumption is correct.

* *Journal I.E.E.*, 1936, vol. 79, p. 15.

There is one small criticism which I should like to make with regard to the number-of-rooms tariff, in which the price paid is the same for each room unless it is a very small one. We have, in some of our mansions, rooms as large as this lecture theatre, which being "private" would be counted as one room only. One might be allowed to suggest, therefore, that there should be an upper maximum as well as a lower minimum as regards the size of room to be charged at the standard price.

Stepped unit charges in tariffs have one disadvantage, which is that a consumer wishing to adopt, say, electric heating, for which the market value of the unit is low, has to consume the unused balance on the upper step price before he comes to the lower step price suitable for this apparatus. As this is a deterrent, I much prefer the usual British method of a fixed charge plus one simple unit charge at a low rate.

I should like to ask whether it is intended that the fixed charge for the farm based on the agricultural area is to cover farm uses such as threshing, and not merely lighting of the farm buildings.

I am interested to note that in Germany the bulk suppliers, who are the equivalent of our Central Electricity Board, are required to see that the distributor can make a living. With the growth of morning peaks it will be necessary for something on the same lines to be done in the near future in this country; otherwise there will be a cessation of the urge to develop certain kinds of load, e.g. space heating and cooking, which, in the joint interests of the community, the Board, and the undertakings, should be encouraged.

In Germany it does not appear to be the practice to hire out apparatus. It is almost the universal experience in this country that far more cookers can be placed by hire than by hire-purchase. I should like to know whether the authors have tried hire schemes in Germany.

I think that the provision of a flat-rate alternative to the two-part tariff is a sign of weakness, and I should like to know why it is offered. We in Mid-Cheshire dispose of 97 % of our domestic sales on the two-part tariff. The flat rate is a nuisance to us, and is obviously of no practical use to the ordinary consumer.

The simple 1d.-a-unit tariffs must clearly be confined to definite kinds of consumers, e.g. a set of workmen's flats or a housing estate; they are not applicable over an area.

I find from the Board of Trade Gas Returns that the gas companies in my area have suffered a reduction in their ordinary consumers but are holding their own by substantial increases in prepayment consumers. Some gas undertakings have eight prepayment consumers to one ordinary consumer. If gas undertakings can secure many new consumers and retain old ones by offering "slot" meters in the face of electricity competition based on quarterly accounts, we should not continue to neglect the "slot" meter.

I agree with regard to the need for better and also for earlier statistics.

Mr. D. J. Bolton: The authors distinguish two stages in tariff unification: first the pattern and then the magnitude. Germany, in her latest enactment, would appear to have covered a large part of the first stage. But there is a still earlier step, and we in Great Britain do not even seem to have taken that. I refer to unification of nomenclature. Until we have standardized our vocabulary we cannot hope to standardize our tariffs. Our present standard glossary, out of several thousand definitions, includes only five tariff terms; and it is high time we added to their number. It should be possible to specify any of the usual tariffs precisely in two words.

Referring to page 572, I think the authors are mistaken in regarding the maximum-demand tariff as the usual British practice for industrial supplies. A reference to published tariffs shows that the block-rate type is equally common, if not more so. Referring to the paper as a whole, it is difficult to draw any general conclusions, but it would appear that the *form* at least of the tariff has very little to do with the costs of supply—it is simply determined by the market which is being aimed at. Another moral which I draw is that it would be perfectly practicable, here and now, for our Government to enact that every distribution undertaking, at least in urban areas, shall forthwith offer its domestic consumers an all-in tariff with a running charge of ½d. a unit. No doubt the backward areas would at first counter this with a heavy fixed charge, but once the framework was established and comparison became possible, public opinion would soon get to work on the latter item.

I am glad that Mr. Kennedy underlined the type of domestic tariff employed in France, and (in this country) in Glasgow and elsewhere. I refer to that in which the first block of energy is sold at a high price and the remainder at a low price, the size of block being dependent on the size of house, etc. Its incidence is almost identical with that of the more usual form of all-in tariff, but it is unique in being entirely self-sufficient and capable of serving domestic needs and meeting legal requirements without any alternatives whatsoever. If, for example, we sell the first block of units per quarter at 4d. per unit and the remainder at ½d., the size of block being a function of rateable value, floor area, or some other factor, there is no need to offer the consumer any options or bother him with any decisions. Automatically he comes on to the low rate as soon as he has consumed his basic "high yield" quota. To overcome the objection mentioned by Mr. Fennell is merely a matter of suitably proportioning the values. Like so many other orphans of the tariff storm, this one has no particular name, and badly needs christening.

Finally, I would suggest that the paragraph heading on page 578 should read "Electricity charges *not* easily adjustable." The authors airily remark that passing on small price variations is "so simple," but if it is so simple as all that, why is it not done? In actual practice a price reduction from ¾d. frequently has to be made to ½d.—a jump of 33⅓ %. The authors' solution of so many units to the shilling has never proved popular, and involves metering and other complications. A much better idea is the "big Kelvin" (= 10 kWh), which can be easily priced in whole numbers of pence.

Miss C. Haslett: I agree with Mr. Townley that more work is needed in explaining to the consumers the tariffs offered by the supply undertaking. We need also to explain to them in an attractive way the running costs of the various domestic appliances.

Regarding the question of the standardization of tariffs, we should be able in the very near future to standardize on a unit charge of ½d., with possible variations in the standing charge. In the early days, standardization of tariffs would not have been advisable, but now that so many people use electricity for a great variety of purposes in the domestic sphere the electrical industry in this country ought to be able to devise an easy way whereby the public may pay for their electricity. If, as seems obvious from the discussion of this paper, there are many difficulties in the way, would not it be possible to appoint a committee on tariffs, and especially on domestic tariffs?

Mr. W. E. Burnand: The uniformity referred to in the paper looks to me as if it is more nominal than real. The German Rules given on page 569 divide consumers into four divisions, one of them with three subdivisions, and, with different ratios of standing to running costs, surely provide diversity enough. There must be room for some further simplification, but it would be bad policy for this not to be related to costs, as advocated in numerous cases. Simplicity that will increase the costly loads and decrease the valuable steady loads is too expensive.

On page 576 it is stated that "the supplier should be in a position to charge what the traffic will bear." This passage is capable of differing interpretations, depending upon who interprets it. I have in mind a tramway which pays 0·75d. per unit where the cost of electricity generation is quite small. The tramway authorities do not consider that to be a fair charge, and it is inclining them to use oil-driven buses instead of electrically-driven tramcars. They are told "The traffic will stand it, and you must pay it." Such an attitude loses electricity supply a great deal of business.

On the same page reference is made to the question of selling electricity by the shillingsworth. This would surely mean special dials on the meter, and any variation in cost would take more arranging than it does now.

To ensure the maximum electricity supply development requires the lowest possible costs and the minimum of restrictions on usage. Every restriction puts a brake upon development, and that is where many tariffs are not as good as they should be.

I should like to refer here to a tariff scheme which I advocated 30 years ago. There are three items: first, a service charge, barely covering the standing costs of the supply; second, a low unit charge, with a discount for quantities; third, a high price per unit, applicable only when the maximum load reaches the safe capacity of the system or the section supplying it. This third item may not be used even once a year, and its object is to ensure that the unimportant load is shut off when the maximum safe supply is reached. An indicator should be supplied to indicate when the maximum charge comes into operation. The simplest way to actuate the system is by means of a ripple on the supply.*

* See *Electrical World*, 1912, vol. 59, p. 261; and *Journal I.E.E.*, 1912, vol. 49, p. 166.

I experimented with this method in 1900 by injecting a small component of about 500 cycles per sec. into a part of the Sheffield electric supply system, with promising results. Two years previously I had invented a frequency meter* and an arrangement whereby it could be used to control distant mechanisms.† A paper by Duddell, Hancock, and Dykes‡ carried the subject still further, but it is only of recent years that the system has come into real use.§ It gives an elasticity which is inherent in no other system. It adapts itself to any variation in time or load factor, or to any emergency. The value of frequency or ripple control is that if any fraction gets through to the control point this remains the same frequency as sent out, being independent of leakage or resistance.

Mr. J. I. Bernard: I should like to refer to the fact that a much lower standing charge and a rather higher unit rate are commonly employed in two-part tariffs on the Continent as compared with our practice here. I have discussed this point with friends on the Continent, and the conclusion to which I have come is that the Continental approach towards complete domestic electrification is a good deal more timid than that which has been adopted in this country; Continental engineers are afraid that if the standing charge is too high people will not adopt the two-part tariff. Moreover, they expect people to use small appliances—toasters, kettles, etc.—which will only use a limited amount of energy corresponding to the first block at medium price in the French tariff and the higher of the two optional rates in the German tariff, before they persuade them to adopt electric cooking or other larger uses. I would point out that whereas the two-part tariff was introduced into this country (at Norwich) about 1910, it is a comparatively recent innovation on the Continent.

The whole position of domestic electrification in this country is far ahead of that in either France or Germany—for example, the proportion of electric cookers and water heaters in relation to the number of consumers or the population is much higher. As regards tariffs, in this country, out of 12 000 000 houses, 6 000 000 are in areas where there is a unit rate of $\frac{1}{2}$d. a unit, 750 000 where the rate is $\frac{5}{8}$d., 1 500 000 where the rate is $\frac{3}{4}$d., and about 1 000 000 in areas (mostly rural) where the unit rate is 1d.; these figures show a greater degree of uniformity than is generally realized.

I should like to support what one or two previous speakers have said, namely that consumers generally do not worry very much about the method of calculating the standing charge under a two-part tariff. What often causes confusion amongst consumers with regard to tariffs is the question of nomenclature. The term "two-part tariff" is a standard one among engineers, but it is extraordinary how often one finds members of the public thinking that a two-part tariff means two flat rates and that a flat rate is a scheme whereby one pays a standing charge per quarter and buys all the energy at a low rate. The remedy is, of course, to use the term "all-in" instead of "two-part" tariff.

The Schufa organization which is referred to in the paper is the only one of its kind in the world. It was built up by Mr. Kauffmann for the purpose of making investigations into the credit standing of customers and prospective customers under hire-purchase agreements. At the time when I had the opportunity of seeing the operation of the organization, they had some 2 million names and addresses of residents of Berlin and district in their card-index, and any supply authority or shop which subscribed to the organization could, for a very small fee, obtain information in regard to the credit standing of any one of those 2 million people in about 3 minutes.

I should like to support the authors' plea for more statistics, or, as I think is probably meant, more detailed field investigation, regarding the characteristics of the domestic load.

Mr. W. J. Cooper: I should like the authors to explain what is meant by the "Economic Group for Electricity Supply." Is it a body like the British Electrical Development Association, but with authority behind it? Or is it like a combination of our Incorporated Association of Electric Power Companies and the British Electrical and Allied Manufacturers' Association with legislative authority behind it? It seems to be a useful kind of organization through which statutory action might be taken. Perhaps the authors will also include in their reply a brief statement of how the electricity supply in Germany is divided as between State ownership, municipal ownership, and company ownership.

I should be glad if the authors would relate the figures given in Table 2 to the earnings of people in Germany. On the basis of 50s. weekly in this country for a person living in a 3-room house as against 25 M. in Berlin for a person living in a similar house, I find that the charge to the person in this country would be $6\frac{1}{2}$ % of his income, and to the person living in Berlin 17 % of his income.

In conclusion, I should like to say that the test of a good legislature is whether it keeps a little ahead of those for whom it is legislating. It is 10 years now since I was associated with a small group who were anxious to adopt a uniform rate of $\frac{1}{2}$d. a unit over a wide area voluntarily. After many hours of discussion we came to the conclusion that it could be done at once if somebody would tell us to do it, because the analysis showed that at the end of the year there was only a few shillings' difference in the total bill under any of about twenty different tariffs. I think that those who are close to the legislature might advise them that the public are getting a little ahead of them, and that it is therefore time that they took some action in this matter.

Mr. R. B. Rowson (*communicated*): An interesting point in the German tariff regulations is that undertakers are empowered to make a fixed charge to cover metering and accounting costs, even when charging under a flat rate. If this were the practice in this country the loss often sustained on low-revenue-yielding consumers would probably be avoided. The provision that consumers are by law compelled to notify their suppliers of changes which would cause their fixed charges to be amended would also merit the attention of future legislation in this country.

If possible, I should like the authors to reply to the following questions:—

(1) Do they think that regulation by means of fixing

* British Patent No. 26723—1898.
† British Patent Application No. 11704—1900.
‡ *Journal I.E.E.*, 1913, vol. 50, p. 240.
§ *Ibid.*, 1938, vol. 83, p. 823.

the retail price is just and is likely, in itself, to achieve the ends usually sought in State regulation—in particular, the best use of capital, avoidance of excessive profits, and healthy development of the industry?

(2) If similar legislation were to be introduced into this country have the authors any statistics to support the suggestion which has been made (not by them) that the follow-on rate should be less than 1d. per unit, assuming that complete domestic electrification is in mind? Would they also think it advisable to include a provision limiting the maximum load a consumer might demand under the statutory tariff?

(3) In the German regulations is there any protection for the bulk supplier who has to make his price such that the distributor can sell at the statutory tariff? (I have in mind that in certain areas it might be possible for capital charges and overhead expenses alone to exceed the revenue received under the State tariff.) Also, what return on capital is allowed before a distributor may approach his bulk supplier for relief?

(4) In this country the incremental fixed charge (per room, per 100 sq. ft., etc.) often decreases with larger houses, but with the Bewag tariff the reverse is the case. Which type of discrimination do the authors favour?

It is pleasing to note that they question the basis on which the fixed charge is usually determined in this country. It is suggested, however, that the block tariff put forward as an alternative does not necessarily overcome the difficulty of making the charge vary with the demand.

As regards the heating load, it is difficult to appreciate how the installation of "more expensive and permanently fitted forms of electric heating appliance" will overcome the physical fact that the load factor during cold weather is, neglecting hours spent in bed, relatively low and thus the load factor of the service used to overcome it must also be low unless the fuel can be stored. The only hope of securing this load seems to be to secure an equally large one in the summer to counterbalance it, but the chances of this appear remote. This is a matter in which existing statistics are of help in visualizing the magnitude of the problem. The estimate of domestic coal consumption given in the Samuel Report may be translated into an equivalent demand for electricity. Taking, say, 15 % efficiency for domestic coal-burning, 100 % for electric heat, a calorific value of 10 000 B.Th.U. per lb. and a load factor of 20 %, one finds that the maximum demand would be about 19 million kW.

One thing which I hope will result from the paper is a concerted effort to gather statistics, so that it will no longer be necessary to guess the diversity. It should not be necessary to go to America for most of our figures, and even when we do it is very difficult indeed to know how to apply them to our conditions. I was sorry, however, that at the meeting one of the authors appeared to question the efforts of those who are trying to attack this problem from considerations of probability. Though admittedly a group of water heaters is not likely to satisfy the condition of being individually and collectively at random over a long period, any diversity figure obtained on this assumption is a useful check and we should regard as suspect any higher figure. Also, in time, we may, like the telephone engineers, be able to concentrate our efforts in the direction of the busy half-hour and arrive at some useful basis on which field tests should be made.

Mr. T. Stevens (*communicated*): With regard to the statement on page 569 that, in Germany, "A flat-rate tariff (with certain qualifications) must be offered as an alternative to the smallest consumers," I should like to ask the following questions: (*a*) Does the German Government require the supplier to serve all "smallest" demands? (*b*) What does the German supplier charge for service connection? (*c*) What proportion of premises in Germany offer "smallest" demands?

It has been stated recently that in Great Britain half the premises offer only the "smallest demands" (minimum 50 units a year, i.e. 10 units summer quarters, 15 units winter quarters).*

[The authors' reply to this discussion will be found on page 589.]

SOUTH MIDLAND CENTRE, AT BIRMINGHAM, 3RD APRIL, 1939

Mr. F. W. Lawton: I do not think that statistics collected from a number of undertakings would be directly applicable to tariffs in a particular case. Undertakings differ in size, character and concentration of load, and in production costs, and so each undertaking should obtain its own statistics of cost for each type of supply. No engineer can escape the obligation of accurately ascertaining the cost of different types of supply in his own undertaking, as it is important that the truth shall be known and compared with existing tariffs. It is reasonably certain that, at present, electricity tariffs are not accurately related to the cost of supply.

Mr. N. M. Hill: Advocates of hire and hire-purchase usually tell us that the credit risk is negligible, but apparently our friends in Germany do not think so. I see from page 573 that they keep back 20 % on any such transaction, and in addition to this they charge a cash discount, which might be 5 %, making a total of 25 % which is just about the usual trade discount. I do not see, therefore, what the contractor gets out of the transaction; perhaps the authors will explain this point.

Mr. H. Long: Houses are usually wired before it is known whether the consumer is going on to the two-part tariff or on to the flat rate. If he chooses the flat rate his lighting service has to be kept separate from his power service, and therefore he has 15-amp. plugs to connect 150-watt appliances and 2-amp. plugs to connect 150-watt lamps. It seems to me that unification and two-part tariffs would be simpler in that respect.

The rateable-value basis of charge has a great deal to commend it, partly because the consumer is already familiar with this basis in connection with his water rate. A basis which is easily understood by the consumer has a

* *Beama Journal*, 1939, vol. 44, p. 86.

great deal to recommend it, even compared with one which may be more academically correct. From the undertaking's point of view a charge on the basis of maximum connected load would be more appropriate, but would of course have the effect of restricting development. Such a restriction of development has occurred in the case of the lighting load in factories in certain areas where there is a tariff which charges 10 % of the power load for lighting at power rates and the remainder of the lighting at about 6d. or 7d. per unit.

Mr. J. R. Blaikie: It is very interesting to learn from the paper that France and Germany are in much the same difficulties as ourselves with regard to electricity tariffs. The outstanding novelty seems to be the German offer of two alternative two-part tariffs, and perhaps the authors will suggest the reason why this has been put forward. If a graph is plotted of these two tariffs, showing overall cost per unit against number of units per annum, the two curves will be found to intersect at a point where the tariffs show the same price per unit, and according to the paper this point occurs at 340 units per annum. The authors say that this is obvious, but I suggest that this critical point is by no means obvious to the ordinary consumer. Why not publish this fact with the tariff, or make a change at this point in the interest of the consumer? By means of about four such changes a tariff can be built up ranging from a few hundred to millions of units per annum per consumer. It is suggested that the time is approaching when it will be possible to regulate the price almost entirely by quantity on a chain of two-part tariffs, and when we shall be able to drop all distinction in regard to the purposes for which the energy is used. With the introduction of all-in tariffs we are already well on the way to this state of affairs, and there are signs that factory hours of working may be staggered to ease the traffic congestion. Whatever may be done in this direction, it will be bound to reflect on electricity supply, tending to flatten out power, traction, and cooking peaks.

It would be interesting if the authors would discuss more fully the German practice of making the unit charge higher than is customary in Great Britain and France; also the effect of bulk-supply tariffs on the consumer's tariff, in particular the British grid tariff in comparison with the German.

Mr. H. Hooper: For many years municipal electricity supply was greatly hindered by the necessity for making contributions to the rates, which prevented undertakings from offering reduced tariffs. On the other hand, to offer electricity at 3 units a penny for domestic purposes, as is now being done in some districts, is economically unsound. Expensive cookers, which could quite conceivably be supplied with electricity at ½d. per unit, are being let out on hire and supplied at ⅓d. per unit. This is hitting the gas companies so badly that in sheer self-defence they are fixing free gas-rings and gas-grillers over the electric cookers, with the result that only the electric oven is being used and the electricity supply authorities are losing the boiling-plate consumption.

Mr. S. T. Allen: The authors refer to the necessity of devising a far more scientific two-part tariff. During the last 30 years, books, articles, and papers by the hundred have been written on this subject, and special committees have considered and reported on it. The result has been that a heterogeneous collection of two-part tariffs have come into being, and, generally speaking, each has been more unscientific than the one which preceded it. The number-of-rooms basis for the fixed charge, to which reference is made in the paper, is surely not scientifically correct, as the number of rooms in a house would seem to have no relation to the effective maximum demand on the undertaking. The selling of electricity has always been wrapped up in a tangle of so-called scientific arguments, and the alternative tariffs have been explained to consumers with the use of terms and conditions far beyond the understanding of the average layman. This has always created suspicion, and has not furthered much the sale of electricity. I think it would be better for us to be more commercial and less scientific when dealing with charges to consumers.

I was one of those who, just 30 years ago, introduced a two-part charge for application to all types of low-voltage consumers (private houses, shops, offices, and works), with a general ½d.-per-unit running charge. My aim was to change the undertaking with which I was associated from a losing to a paying concern, and to afford much larger supplies to the community. I knew my existing costs, and had a pretty close estimate of how they would be affected by the aim I had in mind, which was to double the output of the undertaking in 3 years.

I introduced the rateable-value system of charging, with a ½d.-per-unit rate for domestic supplies, because I considered it would be clearly understood by and acceptable to the average ratepayer, and because I estimated that it would be an easy system for me to adopt and would give the return I required.

In the event of the rateable value not being considered reasonable for the purposes of determining the quarterly rental or fixed charge, such as in the case of small works, I had authority to determine the fixed or rental charge, provided I employed some standard and equitable method. The method I selected was that of taking the standing costs per kilowatt multiplied by the demand in kilowatts (the connected load), and dividing by the diversity factors relating to particular types of apparatus and types of users.

Each individual consumer was then quoted a quarterly rental and a charge of ½d. per unit for all purposes. The consumer entered into an annual agreement which was renewable year by year, and subject to adjustment of the rental due to changes in the apparatus connected.

The output of the undertaking was doubled within 3 years, and a net profit of 10 times more than had ever been made accrued.

The success was partly due, I think, to the personal contacts with the consumers which the new two-part charge necessitated. I am strongly of opinion that one good business-getter in a comparatively small area, who is allowed to get to know all the people necessary in that area, is far more effective than one development officer who is in charge of the business-getting in a large area and has a number of young canvassers to see the persons concerned.

It has been suggested that we should obtain more

statistics to help us, but are not business-getters already spending too much time and effort in obtaining and compiling statistics and returns?

I think that the electricity supply industry is doing very well in regard to business-getting just now, and if a little less pessimism were expressed the general public would more readily appreciate the true position.

[The authors' reply to this discussion will be found on page 589.]

WESTERN CENTRE, AT MONMOUTH, 3RD APRIL, 1939

Mr. L. F. Driscoll: The authors state that while there is a definite tendency towards unification of methods of charging for electricity supplies, the New Rules do not in any way tend to an amalgamation of existing undertakings; and it is surprising to learn that the number of the latter is about equal to that in Great Britain, which in 1934–35 was 576.*

I suggest that in the presentation of such papers as this the foreign coinage and superficial measurements should all be converted into English values.

With reference to Table 1, will the authors please state the approximate monetary values representing the annual wages and salaries of the "wage-earning" and "higher spending power" classes respectively.

Comparing Tariff (A) and Tariff (B), Table 2, it is observed the given consumptions are the same for the three rooms and that the average rate per unit is 1·47d. for the high fixed charge and 1·98d. for the low fixed charge, based on new parity values.

With regard to the monthly collections, are the workmen who read the meters classified as electricians, and, if so, can the authors suggest why they should be lower-paid than the employees who are sent out for collecting after the invoices have been prepared in the office?

Finally, it is rather striking that while the number of rooms has been adopted in Germany as the leading method of establishing fixed charges, the "all-in" tariff position quoted by the authors from D. J. Bolton's paper† shows that only 10 % of 171 undertakings with minimum annual outputs of 10 million units adopt this basis, as against 47 % and 21 % for the rateable-value and floor-area bases respectively.

Mr. J. F. Edgell: In 1924, less than 4 % of the German supply undertakings offered energy to domestic premises on a two-part tariff; by 1936, the figure had increased to 80 %. Since July, 1934, all tariffs and by-laws have had to be submitted, before introduction, for the approval of the President of the Electricity Economy Group; and under such circumstances one would expect very considerable uniformity in the form of the two-part tariff introduced.

I believe the Act of 1938 is the natural result of the Act of 1936, when electricity supply, in common with all other industries, was placed under the Reich Chamber of National Economy. The Act of 1936, in fact, authorized the Minister of National Economy to draw up general or special rules to fix general conditions and tariffs for both gas and electricity, and envisaged a much greater degree of nationalization than has been achieved in Great Britain. The Minister of Economy was empowered to transfer from one supply authority to another, or even to decide whether gas or electricity should be the form of energy used in any particular area, or for any particular purpose. The semi-private (i.e. half Government-owned) undertaking is common in Germany, and the Bewag (Berliner Kraft und Licht A.G.), which supplies practically the whole of Berlin, is a typical example. It is with these facts in mind that we should compare the present conditions in Great Britain with those in Germany.

The actual basis of assessment of the fixed charge is immaterial—the mistake is made when the supply authority attempts to convince the consumer that the basis chosen represents the fixed costs with any degree of accuracy. I suggest that the two-part tariff is best put to the consumer in the form of a step rate tariff, and the basis of assessment of the primary step not discussed. In the undertaking which I represent, 80 % of the domestic consumers have adopted the two-part tariff.

The author rightly gives great credit to the Bewag E³ organization, and I believe he would be justified in stating that Bewag has done good work in increasing the standard of quality of domestic appliances. The Bewag mark on a domestic appliance is regarded as a guarantee of quality, and this undertaking is fast becoming a "proving house" of such appliances.

I note that the two-part tariff is not applicable to the staircases and common rooms, such as wash-houses, of blocks of flats, and this rather suggests that the lighting of such positions is regarded as a landlord's liability—a view that is gaining favour in Great Britain.

I am surprised that in the paper mention is not made of the activities of the German Electrical Development Association (*Arbeitsgemeinschaft zur Förderung der Elektrowirtschaft*) which, under the direction of Dr.-Ing. Mueller, has done so much to popularize the two-part tariff, and at the same time interpret the policy of the Reich Chamber of National Economy.

In Great Britain it is not unknown for pressure to be applied to cause an undertaking to supply energy for certain purposes at an uneconomical figure; in some circumstances a subsidy to meet this exigency has been made available. This, coupled with the fact that the difference in purchase price of energy to two undertakings purchasing equal amounts of energy, but one having a selected station and the other buying direct, is in the region of 6s. per year per head of population, provides reasons for the diverse tariffs which prevail in Great Britain.

In Germany the policy of the Reich Chamber of National Economy is that the fuel or energy best suited to the particular purpose from the national economy point of view shall be the fuel or energy employed, and A.F.E. in interpreting this policy is in contrast with its British contemporary, which sponsors the universal use of electrical energy. This has great influence on tariffs; "necessity" applications of electricity being exploited to subsidize those for which electricity is not the ideal medium from an economic standpoint.

* J. A. Sumner: "Modern Factors Affecting Electricity Costs and Charges," *Journal I.E.E.*, 1937, vol. 81, p. 429, Fig. 1.
† *Journal I.E.E.*, 1938, vol. 82, p. 185.

THE AUTHORS' REPLY TO THE DISCUSSIONS

Messrs. J. W. Beauchamp and **R. Kauffmann** (*in reply*): We would inform Mr. Kennedy that the running charges in the German tariff are generally in excess of cost, and intentionally bear a portion of the fixed charges. In rural areas domestic supplies can be obtained, at the option of the consumer, under the domestic tariff, or, combined with agricultural uses, under the land-area tariff. A charge is made for service connections where these are in excess of a distance limit which varies but is comparatively short. The annual charge per hectare varies with different suppliers and demand conditions. Each supplier decides what class of apparatus he will accept for use on the off-peak tariff.

In reply to Mr. Fennell, in Germany the municipalities own many of the gas undertakings, sometimes operating them through a company. They derive considerable revenue from both the electricity and the gas services, and tend to operate them with a regard for the combined financial result. A dovetailing of these services in accordance with their particular characteristics is also in line with the modern State object of avoiding unnecessary competition.

In the case of agricultural supplies, the annual fixed charge, based on area, covers power and all uses of electricity.

Simple hire of apparatus has been tried to a limited extent; hire-purchase is, however, the general practice.

The "all in" tariff arose after and out of the flat rates, and these remain, but while it had been left (as in Britain) to educational propaganda to teach the consumers to qualify for the advantages of the "all in" method, now the consumer must take the initiative if he wants a flat-rate tariff.

Dealing with Mr. Cooper's contribution, the Economic Group for Electricity Supply represents all the statutory undertakers, membership being compulsory. It concerns itself with technical and other aspects of development and with the conduct of the business, and has such connection with the Government as permits it to act with knowledge of the national policy and to enforce it.

It is not easy to make a comparison between the incomes and standards of living of German and British workers; if the German workers used electricity to the extent which is becoming general in this country, the cost would occupy a much larger percentage of the earnings than is the case here. The relative positions may perhaps be roughly illustrated by saying that the German worker for 20 % more hours receives about 70 % to 80 % of the English wage with which to buy necessaries. These are mostly somewhat dearer than in this country, with the notable exception of housing, which is distinctly cheaper. On the other hand, he enjoys much indirect benefit in the improving equipment of factories, social services, and amenities; taking, so to speak, more in collective benefit and less in individual reward than his British colleague.

Replying to Mr. Stevens, in most German cities 80 % to 95 % of premises are connected. The great bulk, by number, are in the small-user class. A similar problem to our own in regard to cost of connection and small revenue exists there also, and has not yet been met by enlarging consumption to the extent it has here.

In reply to Mr. Blaikie, it is left to the user to ask to be transferred from his first selected tariff to the alternative.

Mr. Driscoll is correct in assuming that the meter readers are electricians. Those who collect receive somewhat higher pay, as is usual in business where a cash responsibility is added to other qualifications.

In the last paragraphs of his contribution Mr. Edgell is presumably referring to arrangements which have occasionally been made in agreement with the supply undertakers for loads of considerable magnitude or having "off peak" or other special features to be supplied at rates which, whilst low, are in excess of the incremental cost of the supply. This action has benefited industry by saving owners the cares of private generation and has assisted the suppliers (or groups of them) by increasing the scale of their operations, improving the form of their load curves, and generally tending to lift the public supplies on to a plane of greater usefulness with earlier possibilities of using larger and more economical plant. The price at which selected-station owners buy energy varies very much with local conditions and their past history. More uniformity will arise as they all become modernized and their local load reaches values which call for, or would, under independent operation, have called for, a plant of the first magnitude. The supplier who owns a non-selected station, or relies entirely upon bulk purchase, is now able to obtain supplies at the average cost, adjusted to his demand conditions, over large areas in which the supply services are growing and being modernized very rapidly. There is no evidence to suggest that under independent and isolated operation the divergence in tariff scales between the large and the small suppliers would have been less than it is at present, whilst they are all now depending on a system of collective generation which has effected great economies in the face of rising costs of plant and fuel.

It will be appreciated that the German and French efforts to standardize tariff forms are of recent date, and details of their operation have not yet been fully evolved or stood the test of practice.

A few of the questions which were raised in the discussions are matters rather for the statesman than for the supply engineer. We feel that such questions would be better left to those advisory bodies of the industry to whom authority is apt to look for guidance when contemplating action.

TESTING OF TRANSMISSION-LINE INSULATORS UNDER DEPOSIT CONDITIONS*

By PROFESSOR W. J. JOHN, B.Sc., Member,† and C. H. W. CLARK, Ph.D., Graduate.‡

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SUMMARY

After an Introduction setting out the general problem of atmospheric pollution in relation to transmission-line insulators, the authors deal in Part I with the development of a saline-deposit test for such insulators. The production in the laboratory of wind and of salt spray is discussed, and a comparison is drawn between natural and artificial dew formation. Means of judging the severity of dew formation and of deposit formation are described, and standard tests outlined. An account is given of the various types of insulators tested and of their behaviour under test.

Part II of the paper is devoted to an investigation of the possibility of protecting insulator surfaces from industrial and saline deposits. The protective action of a cylinder, and of a cylinder and disc in combination, are examined, and a description follows of the design and performance of a 33-kV insulator embodying a cylinder and a disc.

In Part III the authors describe an inquiry into the formation of industrial deposits under natural conditions. Visual observations have been made of the deposit formation on insulators hung from a gantry on the roof of a laboratory in East London, and the leakage-current variations due to changes in weather conditions have been measured by a special form of recorder. The test-results obtained on different insulator types are compared, and some interesting conclusions are drawn from the discharges observed on the insulators during bad weather.

INTRODUCTION

In London and other large cities, solid deposits settle from the atmosphere at an average rate of about 1 ton per day per square mile, while at certain times of the year the rate may be about three times as great. In certain localities, e.g. in the immediate vicinity of large power stations, the rate of deposition may be much higher.§ The usual deposit mainly consists of waste products formed by the combustion of coal, but in certain districts it contains also the waste from chemical or cement works, blast-furnaces, etc. It consists, therefore, partly of free carbon and partly of metallic salts in various amounts. Such deposits have a comparatively high electrical resistance while dry, owing to their powdery nature, but when they become moist the salts go into solution and the resulting damp deposit is a much better conductor.

The outdoor insulators used on overhead power lines and associated apparatus are exposed to these deposits, and trouble has frequently been experienced due to the presence of the deposits on insulator surfaces. A similar problem occurs near the sea coast, where the insulators are subjected to deposits of sea-salt, since these also form a conducting solution when moist. In Great Britain, which is a highly industrialized island, both salt and industrial deposits present serious problems.

The surface of a clean dry insulator has a certain conductivity under normal conditions:§ when the surface is dirty and moist this conductivity is increased. The immediate effect of this is an increased loss of power due to the leakage current. A more serious effect is that it frequently causes a reduction of the flashover voltage of the insulator. When an insulator surface has a heavy industrial or salt deposit and this is made moist by dew or mist (which wets the underneath as well as top surfaces) flashover of the insulator often takes place at working voltage.‖

Several designs of insulator have been suggested for use under deposit conditions,¶ and it is generally agreed that these give a better performance than the old types. Tests have been described for comparing the performance of insulators under both industrial and salt deposits, either under natural conditions or in the laboratory.**

Tests made under natural conditions are slow in yielding results, and it would be helpful if laboratory methods of testing were available of such a nature that insulator performance under deposit conditions could be rapidly judged. Such tests should enable different types of insulator to be compared and new and improved types to be evolved. The formation of industrial deposits is a slow process affected by many factors, and the deposit itself, while consisting mainly of soot, is of complex composition. Salt deposits, however, are simpler in their composition and quicker in forming. In the present work it was found possible to form an artificial saline deposit in the laboratory under controlled conditions which approximated sufficiently nearly to natural conditions.

Various criteria for judging the insulator performance were considered. It was found that the best criterion was that advocated by Forrest,†† namely the magnitude of the leakage current.

PART I

DEVELOPMENT OF A STANDARD SALINE-DEPOSIT TEST FOR INSULATORS

In practice, when salt is deposited on line insulators it is carried to the insulators by a wind blowing off the sea. Even a light wind will carry some salt, but a strong

* This paper contains the subject matter of a thesis presented by Dr. Clark to the University of London for the Ph.D. degree.
† University of London, Queen Mary College.
‡ Steatite and Porcelain Products, Ltd.
§ See Bibliography, (1).
§ See Bibliography, (14).
‖ *Ibid.*, (2), (3), (5), (7), (8), (13), and (18).
¶ *Ibid.*, (6), (7), (8), (10), (11), (12), and (19).
** *Ibid.*, (4), (9), (11), (12), and (19).
†† *Ibid.*, (4).

wind will take up more spray from the sea, and will also be able to carry larger particles and to carry them farther. Thus the stronger the wind, the more rapidly will insulators near the sea be affected and the farther inland will salt effects be noticed. Hence, in laboratory testing, the first essential for forming a deposit must be apparatus which produces a salt-laden wind. Moreover, in order to imitate natural conditions under which dangerous deposits are quickly formed, it should produce a uniform flow of air over the whole insulator at a high velocity, say from 20 to 60 m.p.h.

Dry deposit is not dangerous, and the second essential must be apparatus for "wetting" the deposit by artificial dew formation. Sea-salt will always absorb a certain amount of moisture from the atmosphere since it contains magnesium chloride, a very hygroscopic material. On an insulator, this moistening is partly counteracted by the drying action of the leakage current, and the effect of the salt deposit only becomes serious when the humidity is very high. It is naturally most serious when the humidity is so high that moisture is deposited on the insulator in the form of dew.

Production of Wind

The wind was produced by a wind-tunnel as used in aeronautical engineering. Preliminary tests were made in a small wind-tunnel of the usual type consisting of a wooden channel 16 in. square in cross-section, through which air was drawn by a fan. A small atomizer was placed in the entrance to the tunnel, and the spray formed by it was drawn by the wind over the insulator. After preliminary tests a new wind-tunnel was designed to permit the testing of large 33-kV pin insulators.

Fig. 1 shows the new wind-tunnel, which was of the "open jet" type. The jet had a circular cross-section, 3 ft. in diameter at the back, and narrowed down to an oval orifice 3 ft. high by 18 in. wide at the front. The cylinder in which the fan revolved was 3 ft. in diameter by 1 ft. long, and was attached to the back of the jet. The fan was direct-coupled to a motor and at full speed absorbed about 2 h.p. The open-jet type of wind-tunnel usually has a closed circuit, the air which issues from the jet being collected and returned by a suitable channel to the fan. It is thereby possible to obtain a higher wind-velocity for the same power. Because of the high cost of such a wind-tunnel and the space which it would occupy, the return channel was not provided and the air, after passing the insulator, went through an open window to the outside of the laboratory. The two parts of the wind-tunnel were, however, so designed that they could be incorporated in a closed-circuit wind-tunnel at a later date.*

As is well known in aeronautical engineering, special precautions are necessary if an approximately uniform wind velocity is to be obtained over the full section. For this reason the fan blades were tapered from a width of 6 in. at their smallest diameter to 1 in. at their tips, and a wooden cone was supported by stationary sheet-iron fins with its large end (which was 10 in. in diameter) immediately in front of the centre of the fan.

The insulator was supported outside the wind tunnel immediately in front of the jet orifice, thus giving free access for the high-voltage lead. Moreover, since the jet was 3 ft. high by 18 in. wide, the apparatus was suitable for the largest types of pin insulator and for short strings of suspension insulators.

The maximum wind velocity, as measured by means of a Pitot tube and differential manometer, was about 30 m.p.h. Lower velocities could be obtained by reducing the motor speed.

Imitation of Various Wind Conditions

At the height above ground level at which an insulator is usually installed, the wind normally has a fairly uniform streamline flow. It may blow in any direction;

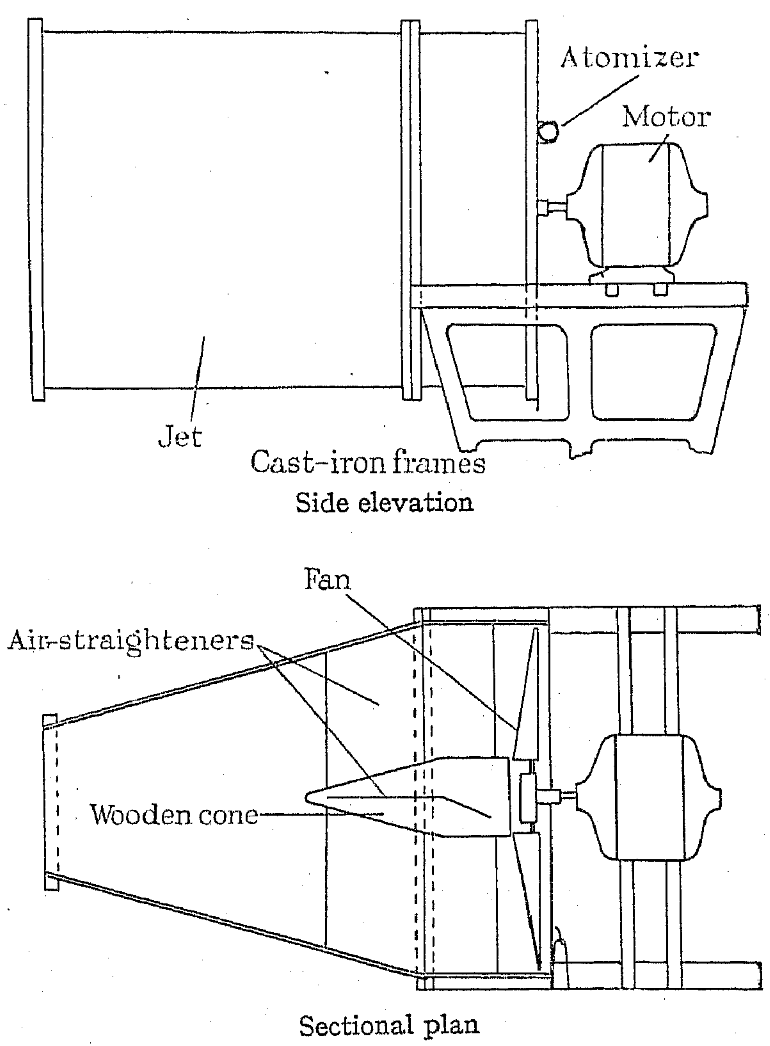


Fig. 1.—New wind-tunnel.
Scale: $\frac{1}{24}$ full size.

wind coming directly from the sea will contain most salt, but wind from slightly different directions will also carry some salt. These conditions can be imitated in the laboratory by turning the insulator about its vertical axis. The insulator is allowed to remain at selected angles for short times during each test. In most of the tests about to be described, the insulator was allowed to face one direction during 80 % of the total testing time. It was then turned through 45°, first to the right and then to the left, for the remainder of the test. Conditions for an insulator on a small island where salt-carrying winds come from all directions can be imitated by turning the insulator slowly about its own axis throughout the test.

* This has not been done, but an improved tunnel, using a closed circuit, has been made and is now in use.

Another phenomenon which probably occurs from time to time is the formation of large eddies which will subject the insulator to gusts of wind at various angles to the horizontal. Such gusts may blow at any inclination, from horizontal to vertical, according to the position of the insulator in the eddy, and will have a very serious effect on the insulator by carrying deposit into the grooves and recesses under the sheds. In order to imitate these conditions, the insulator was arranged so that it could be inclined to the wind-stream from the tunnel. For this purpose, the cross-arm to which the insulator was fixed was hung from two cranked steel rods which could swing in brass bearings, and a cord wound on to a drum by a small motor was arranged to pull the insulator slowly round from the vertical position to the horizontal. The speed of the motor could be varied and was usually adjusted so that the insulator was raised from the vertical to the horizontal in 1 minute; the motor was then reversed and allowed the insulator to return slowly to the vertical. This slow tilting between the vertical and the horizontal will be referred to as " nodding."

Salt-Spray Formation

The spray was formed by an atomizer. This consisted of a brass tube, $\frac{1}{16}$ in. bore and 4 in. long, which dipped into sea-salt solution and had a jet of air directed across its top end. The sea-salt solution was contained in a bottle holding 250 cm^3, and this quantity could be atomized in about 15 min. The spray had the appearance of mist when it left the atomizer, but part of it collected on the fan blades and other parts of the wind-tunnel and was subsequently blown off as drops. The size of the particles blown against the insulator therefore varied from very small, mist-like particles, to drops about $\frac{1}{8}$ in. in diameter. The appearance of the deposit formed on the insulator depended chiefly on the humidity; if this was high the salt remained wet and even ran down the sloping surfaces and dripped off. When the humidity was low the salt dried rapidly, forming a white crystalline coating on the insulator.

Dew Formation

In order that dew may form on an insulator, its temperature must be below the dew-point of the surrounding air. Natural formation of dew usually occurs on a cold night when the sky is clear. During the day the heat of the sun causes evaporation from rivers, the sea, etc., and the water vapour remains in the air adjacent to the earth, increasing its humidity. After sunset, solid bodies begin to radiate heat into space, and their temperature falls. The temperature falls most rapidly in the case of well-exposed bodies which have a good radiating surface and a small capacity for heat. On a dull and cloudy night conditions are not good for radiation, as the radiant heat is reflected back by the clouds. Given the conditions of a clear night and high humidity, an insulator experiences a rapid deposition of dew since it is well exposed, has a large surface of good radiating material, and its capacity for heat is not very large. Its temperature therefore falls rapidly until it reaches the dew-point, when moisture from the air begins to condense on the insulator. After this an equilibrium condition is probably set up, the temperature of the insulator remaining just below the dew-point with the heat radiated to space being compensated by the latent heat given up by the water which condenses as dew. There will be a continuous deposition of dew until the humidity of the air has fallen too low or else until radiation from the insulator ceases, as it does, for example, at sunrise.

As a first attempt to imitate natural dew formation, the insulator was kept in the small wind-tunnel, which was then in use; the fan was stopped and the central portion of the tunnel, which had a glass window through which the insulator could be observed, was divided off by wooden partitions. The space so formed was filled with steam by means of a small boiler, but even when

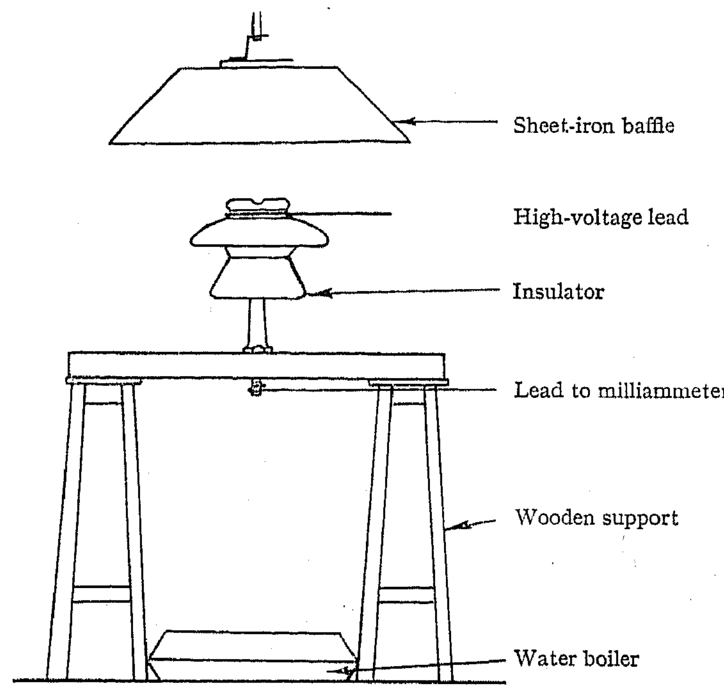


Fig. 2.—Diagram of dew-forming apparatus.
Scale: $\frac{1}{20}$ full size.

the insulator was first cooled in an ice-box only a temporary deposit of moisture was formed. The insulator rapidly attained a temperature sufficiently high to prevent any further dew formation because it had no low-temperature surroundings to which to radiate the heat given to it by the surrounding air and by the steam which had condensed on it.

A new method of forming dew was therefore developed in which the insulator was not previously cooled but was exposed as much as possible, so that any tendency for its temperature to rise could be checked by radiation. The temperature and humidity of the air in its immediate vicinity were raised until the dew-point rose above the temperature of the insulator. This was accomplished by boiling water in a flat tray placed below the insulator. The steam from this rose over the insulator and was reflected down again by a sheet-iron baffle which was hung above the insulator. This ensured an eddying cloud of warm moist air round the insulator and formed a heavy deposit of moisture both underneath and on top of its sheds (Fig. 2).

In Table 1 a summary is given comparing natural and artificial dew-formation.

Table 1

COMPARISON OF NATURAL AND ARTIFICIAL DEW-FORMATION

Natural dew.

Insulator loses heat by:—	Insulator gains heat by:—
Radiation into space through more or less transparent atmosphere	(i) Latent heat of condensation of dew (ii) Contact with air at temperature of dew-point or higher (iii) Heating due to leakage current

Equilibrium set up with continuous deposition of dew.

Dew formation in the laboratory.

(*a*) *Ice-box Method*

Insulator loses heat by:—	Insulator gains heat by:—
No losses (insulator cooled in ice box before test)	(i) Latent heat of condensation of dew (ii) Contact with air at temperature of dew-point or higher (iii) Heating due to leakage current (iv) Radiation from surroundings

Temperature of insulator rises rapidly, deposition of dew for short time only.

(*b*) *Method Used in Present Work*

Insulator loses heat by:—	Insulator gains heat by:—
Radiation to relatively cold surroundings	(i) Latent heat of steam (ii) Contact with air at temperature of dew-point (iii) Heating by leakage current

Equilibrium set up as in natural dew-formation, continuous deposition of dew.

Method (*b*) is undoubtedly a nearer approach to natural dew-formation than Method (*a*). It cannot, however, be regarded as exactly reproducing natural dew, because the difference in temperature between the insulator and the surrounding air is obtained by raising the air temperature instead of by cooling the insulator. The whole process takes place, therefore, at a higher temperature than that at which dew normally forms. There are, moreover, difficulties in making sure that the warm moist air comes into contact with all parts of the insulator, but these can be overcome to a large extent by a suitable design of the dew-forming apparatus.

Electrical Equipment

The high-voltage supply and the measuring equipment were arranged as shown in Figs. 3A and 3B. The insulator pin was insulated by its wooden supporting structure, but was connected to earth through the milliammeter and a variable resistor. The voltage drop across the

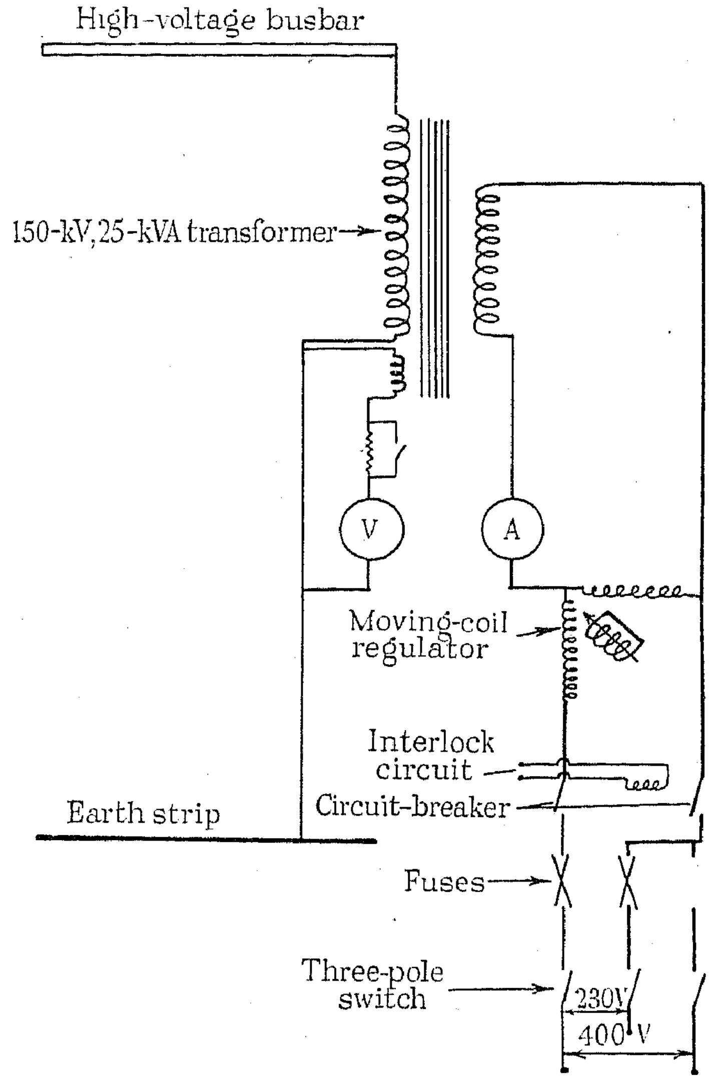


Fig. 3A

latter was applied to one pair of plates of a low-voltage cathode-ray oscillograph so as to produce a vertical deflection proportional to the leakage current. The other pair of plates could be connected either to the oscillograph time-base or to the voltmeter winding on the transformer. The leakage-current oscillograms could

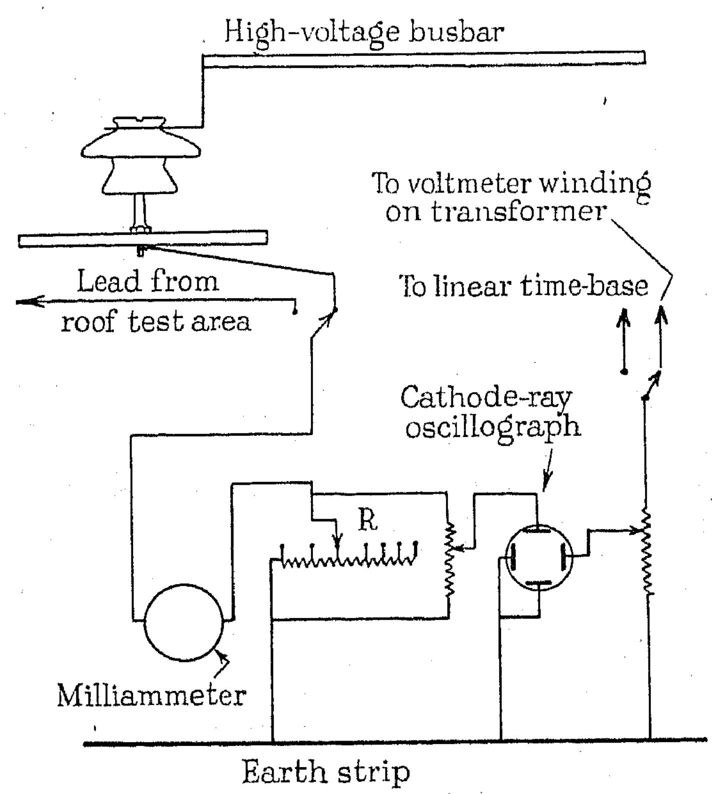


Fig. 3B

therefore be shown either on a time-base or on a base proportional to the voltage applied to the insulator. The voltage-base was most often used, as it showed departures from the sinusoidal wave-form better and also showed the phase relation between the current and voltage. The milliammeter was a rectifier type with a switch for varying the range from 0·35 to 35 milliamp. for full-scale deflection. The smallest current which could be read on it was 0·05 milliamp.

This equipment was used for making measurements of the leakage current at working voltage. For flash-over and other tests at voltages above working voltage, the lead to the meters was disconnected and the pin of the insulator was connected directly to the earth strip.

Choice of Suitable Severity for Laboratory Tests

The apparatus for forming a deposit and also for forming dew having been developed, it was necessary to decide on a suitable severity for the tests so as to reproduce natural conditions as nearly as possible.

The severity of the dew depends on the temperature and humidity of the air surrounding the insulator, and could be controlled by varying the rate at which steam was generated in the dew-forming apparatus. This depended on the power input to the heater used for boiling the water, and the severity of the dew test will be described by reference to the power input to the steam generator.

As the severity of the salt deposit could be varied in several ways while that of the dew depended on one factor only, it was decided to standardize the dew severity first. The standard dew severity could then be used in tests made with the object of determining a suitable severity for the salt deposit.

Choice of Suitable Severity for Dew Tests

The 33-kV line insulator Type P.3 (see Fig. 6) was given an arbitrarily chosen salt deposit and subjected to dew tests of various severities. For this purpose the input to the steam generator was varied between 1·8 and 4·8 kW. The deposit on the insulator was a severe one, formed in each test by atomizing 250 cm^3 of salt solution in approximately 12 minutes. Upward currents of air were imitated by nodding the insulator between the vertical and horizontal for 2 minutes during each test. Two tests were made with each severity of dew, and leakage-current surges of 15 milliamp. or more were observed for each severity in at least one of the tests. The results are tabulated in Table 2.

From a consideration of the leakage-current surges the condition of the insulator appears to have been worst with the third severity of dew, 3·2 kW, although its condition was nearly as bad for dew formation with either 3·9 or 2·5 kW input. When the dew severity corresponded to 4·7 kW input its condition seemed somewhat better, although the improvement is not very marked. With dew corresponding to 1·8 kW input its condition was definitely better, but the effect may have been a reduction of the frequency with which the surges occurred rather than a reduction of their magnitude, since one heavy surge was recorded.

The maximum voltage which could be applied to the insulator was also lowest for a dew severity corresponding to 3·2 kW, being then only 25 kV. With dew severity corresponding to 1·8 kW the maximum voltage was 40 to 45 kV, while for the other severities it was between 28 and 35 kV. For all tests, except those with dew formation at 1·8 kW input, arcing discharges were observed during several minutes; during the two tests with 1·8 kW input only a single arc was observed. It was decided to use an input of 3·2 kW to give the standard severity of dew in all future tests. It appears, however, that small variations in the input to the steam generator will not have a serious effect on the results of the tests.

Table 2

EFFECT ON INSULATOR PERFORMANCE OF VARIATION IN AMOUNT OF DEW DEPOSITED

Insulator type, P.3; voltage, 20 kV; salt deposit, 250 cm^3 of salt solution, atomized in approximately 12 minutes. Upward air currents imitated by " nodding " the insulator through 90° for 2 minutes.

Severity of dew, expressed as kW input to heater	Maximum leakage-current surge at working voltage		Nature of discharge observed on insulator at working voltage		Voltage at which leakage current exceeds 50 mA (circuit-breaker trips), Test 2
	Test 1	Test 2	Test 1	Test 2	
	mA	mA			kV
1·8	1·8	20	Audible only	Sparking round pin. Arc for few seconds	45
2·5	15	12	Arcing on top shed	Arcing round pin	35
3·2	7	25	Arcing round pin	Arcing on top shed and round pin	25
3·9	14	17	Arcing round pin	Arcing round pin	28
4·7	8	15	Arcing round pin	Arcing round pin	30

Choice of Suitable Severity of Deposit

(a) Effect of quantity of salt.

The effect of the quantity of salt deposited on the insulator was next studied. It was decided that the best measure of severity would be the actual quantity of salt atomized, and a definite amount of concentrated salt solution was measured out into the atomizer and the test continued until it had all been used.

Table 3

SALT TEST ON INSULATOR P.3: VARIATION OF QUANTITY OF SALT SOLUTION SPRAYED

Insulator vertical. Standard dew severity (3·2 kW)

Volume of solution sprayed	At working voltage (20 kV)		Over-voltage, i.e. voltage at which leakage current exceeds 50 mA (circuit-breaker trips)
	Maximum leakage-current surge	Discharges	
cm^3	mA		kV
None	0·8	Faintly audible	65 (flashover)
125	3	Audible	45
250	4	Audible	35
500	6	Arcing round pin	27
1 000	10	Arcing round pin	25
2 000	25	Arcing round pin	25

Table 3 shows the results of a series of tests in which different quantities of solution were used to form the deposit. In all tests the insulator was vertical during the whole time of formation of the deposit and faced in one direction most of the time, but was turned through 45° to the right and to the left for short periods. The conditions imitated were therefore salt spray carried in a horizontal wind mainly from one direction but veering for short times through 45°.

As the quantity of salt was increased the leakage-current surges increased and the discharges first became louder and then became visible as arcs round the pin. At the same time the maximum voltage which could be applied to the insulator decreased. In the last test, with a deposit formed from 2 000 cm^3 of solution, the leakage current surged up to 25 milliamp. and might have been heavy enough to lead to complete flashover if the insulator had been connected to a power transformer.

(b) Effect of wind inclination.

The effect of wind inclination, as imitated by "nodding" the insulator during the formation of the deposit, is shown in Table 4. The effect of a period of nodding less than 1 minute is not very pronounced, and the maximum leakage current observed was 4·5 milliamp. compared with 3·5 to 4 milliamp. when the deposit was formed without nodding. When the insulator was nodded for longer periods the effect was more serious, and after 90 sec. of nodding the maximum current surge obtained was 7 milliamp. After 2 min. of nodding a maximum surge of 25 milliamp. was obtained. When the period of nodding was still further increased the severity of the deposit began to decrease again, possibly because the time during which the insulator was vertical was appreciably smaller and the deposit which normally forms on the sloping tops of the sheds was reduced. When the time of nodding was 5 min. (nearly half of the total time of 12 min. during which the deposit was formed) the maximum surge observed was 12 milliamp.

(c) Effect of wind direction.

The worst trouble from salt deposits is experienced on small islands where the insulators are exposed to salt-bearing winds blowing from all directions, and a series of tests was made to determine whether the deposit formed by a given amount of salt blown on to the insulator from one direction only was worse than that formed by blowing the same amount of salt on to the insulator from all directions. The insulator was first allowed to face in the same direction during the whole time of formation of the deposit, which was about 15 min. It was next allowed to face in one direction during most of the time of formation, but was turned through 45° first to the left and then to the right for periods of 1 minute each. Finally, it was turned through 90° every 2 minutes throughout the period of formation of the deposit. The results show that, for the same quantity of deposit, the condition of the insulator is made no worse by deposit-bearing winds coming from all directions than by a wind from one direction only. It may be concluded that the increased severity of the deposit formed on insulators situated on an island is due to the increased amount of salt deposited and not to the fact

Table 4

SALT TESTS ON PIN INSULATOR P.3: VARIATION OF TIME OF "NODDING"

Salt deposit formed from 250 cm^3 of solution. Standard dew severity (3·2 kW)

Time of "nodding" between vertical and horizontal positions	At working voltage (20 kV)		Over-voltage, i.e. voltage at which leakage current exceeds 50 mA (circuit-breaker trips)
	Maximum leakage-current surge	Discharges	
	mA		kV
0	4	Audible	28
25 sec.	4·5	Audible	35
50 sec.	4·5	Sparking around pin	35
90 sec.	7	Sparking around pin	30
2 min.	25	Arc from conductor and from pin	25
$2\frac{1}{2}$ min.	15	Arc from conductor and from pin	30
5 min.	12	Arc from pin	30

that it is distributed round the insulator. It is therefore permissible to carry out all tests with the insulator facing in one direction during the formation of the deposit. Actually, for most of the tests in the present work the conditions imitated were those in which most of the salt is carried in a wind from one direction and smaller quantities are carried by winds from adjacent directions.

Consistency of Test Results

It was found in the tests which were made to determine a suitable severity of dew that the results could not be accurately repeated even when the conditions of formation of the deposit and dew were repeated as accurately as possible. Subsequent tests to investigate the effects of other variables confirm this, although the results of tests with less severe deposits show better uniformity. For example, in tests made on various dates with deposits formed by atomizing 250 cm³ of solution with the insulator vertical, maximum leakage-current surges in five tests ranged from 3·5 to 4·5 milliamp. This is a much smaller range than that shown by the results of tests in which the deposit was made more severe by nodding the insulator. Here the variation is from 7 to 25 milliamp. in three tests. The values of the maximum voltage which could be applied to the insulator vary over a large range even in the tests with the less severe deposit, the extreme values being 27 and 45 kV. The severity of discharge observed on the insulators also varies, and corresponds generally with the magnitude of the leakage-current surges.

Standard Tests

As a result of the experiments just described it was decided that tests for comparing the performance of different insulators should be made with deposits formed in three different ways, as follows:—

(1) A not very severe deposit formed by atomizing 250 cm³ of concentrated sea-salt solution, the insulator remaining vertical so as to imitate a horizontal wind.

(2) A more severe deposit formed by atomizing 1 000 cm³ of solution, the insulator being vertical.

(3) A deposit formed by atomizing 250 cm³ of solution, the insulator being nodded between the vertical and the horizontal for approximately 20 % of the total time of formation of the deposit.

Behaviour of Insulator during Tests. Criteria for Judging Insulator Performance

The way in which the leakage current of an insulator varies during a typical dew test is shown graphically in Fig. 4. At first the leakage current increases steadily, and the graph is a single line. Later it becomes unsteady, and the graph separates into two lines representing the limits between which the current is surging.

Oscillographic records of the wave-shape of the leakage currents were photographed, and Fig. 5 (see Plate 1, facing page 600) shows some typical oscillograms. No. 1 shows the leakage current of Insulator P.2 and was taken before dew began to form, the leakage current then being 0·15 milliamp. The short-duration current peaks shown at one end of the oscillogram were usually observed when the insulator was dry. They did not occur at the same point in each cycle, and could only be photographed with an exposure of 1 or 2 cycles. They were probably due to sparking between the conductor and the neighbouring porcelain surface. They disappeared as soon as dew began to form. Such oscillograms show that dry insulators act as almost pure capacitances, the maximum current occurring at the point of zero voltage. Later in the cycle, however, the current rises to a second peak at the point of maximum voltage. It will be seen from subsequent oscillograms that as the dew forms this second current peak grows. It is interesting to note that the leakage current of a dry insulator has practically the same magnitude and the same wave-form whether the insulator has a salt deposit on it or not. Only if the relative humidity of the air exceeds about 80 % does the deposit become moist enough to have an appreciable conductivity.

As dew forms on the insulator its leakage current increases and the oscillogram becomes elongated (No. 2, Fig. 5). When the leakage current reaches about 1 milliamp. it becomes unsteady, and oscillograms

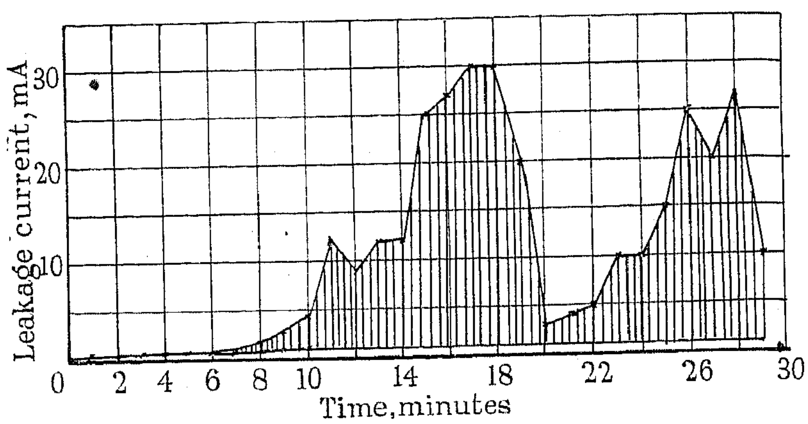


Fig. 4.—Dew test on P.2 pin insulator. Variation of leakage current during test.

similar to No. 3 are obtained (the example shown was given two exposures at an interval of a few seconds). These oscillograms show that the resistance component of the insulator impedance is not "pure" but varies with the applied voltage. On a time-base the oscillogram appears approximately sinusoidal.

As the dew deposit gets heavier the leakage current increases, until its heating effect causes the moisture film over the surface of the insulator to become unstable. The result is that the insulator surface becomes dry in places and high-resistance dry areas are formed separating the moist conducting areas, and these moist areas then act as the plates of a condenser. The more uniform voltage distribution, which existed over the surface of the insulator while the moisture film was continuous, is replaced by one due to low-resistance surfaces, across which there is only a small voltage-drop, alternating with high-resistance surfaces over which most of the voltage drop occurs. The effect of this is shown by the oscillogram in two ways. Firstly, there is an increase in the out-of-phase or capacitance component of the current as shown by the increased height of the oscillogram at the centre, i.e. the point of zero voltage. Secondly, intermittent discharges occur at the instants of maximum voltage across the highly stressed dry

areas, causing increases of current which show as peaks at the ends of the oscillograms. Oscillogram No. 4 was taken during a small current surge. During heavy surges the oscillograms vary from cycle to cycle. Breakdown occurs at about maximum voltage and the current rises very rapidly; the oscillogram is of the same form as No. 4, but the peaks at the ends are large compared with the loop at the centre. The surge may last a few cycles or a few seconds. Between surges the oscillogram may be similar to No. 3 or No. 4.

The breakdown which the oscillogram shows is visible as a discharge on the insulator surface. When the leakage current is small the discharge consists of a glow or small sparks near the electrodes of the insulator or at isolated parts of its surface. At higher currents the sparks become easily visible and audible. They are blue, and appear to occur simultaneously in several places. At still higher currents the sparks unite into a single yellow arc. The most usual position for the discharge is around the pin under the bottom shed. It is sometimes observed on the sheds and sometimes between sheds.

This study of the shape of the oscillograms and the nature of the discharges occurring on the insulator, supports the conclusions reached by considering leakage-current surges. It was decided to accept the magnitude of the leakage-current surges as being the best criterion by which to judge an insulator during laboratory salt-deposit tests. This is a numerical quantity which can be measured by means of a comparatively simple instrument, and is a criterion which has been used by other workers.*

The only other numerical criterion is the maximum voltage which can be applied to the insulator before failure occurs. In these tests the tripping of the circuit-breaker due to an excessive leakage-current limited the maximum voltage, and so the criterion was also in effect a measurement of leakage current. It suffers, moreover, from the disadvantage that the test is conducted at a voltage above working voltage and subjects the insulator to a condition which will not occur in practice. The over-voltage test would have more importance if the transformer impedance were lower, so that flashover could occur. The criterion would then be the flashover voltage. The test would correspond to possible natural conditions if it consisted of a measurement of the surge which had to be superimposed on the continuously applied working voltage in order to produce flashover. It would then imitate the effect of switching surges.

Insulators Tested

The eight pin-type insulators which were available for tests are illustrated in Fig. 6. The relevant particulars of the various insulators are given in Table 5. With the exception of P.1 (which is for a working voltage of 11 kV), all are 33-kV insulators. P.2 is an old design and is small for 33 kV as judged by present practice. P.3 insulators are known to have behaved badly under salt conditions, and P.4 insulators gave improved performance under some of the conditions for which P.3 were not satisfactory. The last four (P.5, P.6, P.7, and P.8) are specially designed for salt-deposit conditions, and are claimed to give better performance than the other designs.

* See Bibliography, (4).

Comparison of Pin-insulator Performance

The eight pin insulators shown in Fig. 6 were tested by the method now developed. Table 6 summarizes the results of tests using the three standard severities of deposit. A consideration of these results places the insulators in the following order of merit: P.1, P.7, P.8, P.5 and P.6, P.4, P.3, P.2.

In all the tests P.1 behaved well. It behaved particularly well under deposits formed with a horizontal wind, and did not seem to be much more affected by a deposit formed from 1 000 cm³ of solution than by one formed from 250 cm³. Nodding the insulator so as to imitate upward air currents produced a more severe deposit, although even then the leakage current only surged to 2 milliamp., and a voltage of 3½ times the working voltage could be applied to the insulator before the current became large enough to cause the circuit-breaker to trip.

Table 5

PARTICULARS OF PIN-TYPE INSULATORS

Type	Shed diameters (in.) Top	Middle	Bottom	Creepage distance*	Surface-resistance coefficient†	Flashover distance‡ (dry)	Flashover voltage (dry)
				in.		in.	kV
P.1	7	—	4½	13¾	1·20	4·9	63
P.2	9½	—	8	15¾	0·94	10·3	110
P.3	10½	—	8¼	17	1·0	13	113
P.4	10½	—	6½	20½	1·41	11·1	108
P.5	10½	9½	9	31½	1·7	13·8	136
P.6	12	10	9	35¼	1·76	14·2	150
P.7	All sheds 8½ in. diam.			38¼	2·32	14·0	148
P.8	All sheds 9 in. diam.			33¼	2·31	14·3	138

* The creepage distance is the shortest distance along the insulator surface between the two electrodes of the insulator.
† The surface-resistance coefficient is the resistance which would exist over the insulator surface between conductor and pin if the surface were covered with a uniform deposit of such material and thickness that the resistance between opposite edges of a square flake of the deposit was 1 ohm.
‡ The flashover distance is the shortest distance through air between the conductor and pin or supporting cross-arm.

Of the 33-kV insulators, P.7 is the best from all points of view. With deposits formed in the three different ways the maximum leakage-current surges were 1·35, 1·8, and 2·0 milliamp., showing that the condition of the insulator is not made much worse either by comparatively large quantities of salt or by upward air currents. In the over-voltage tests a voltage of from 3 to 4 times the working voltage could be applied before the circuit-breaker tripped. P.8 is similar to P.7 but has three sheds instead of four, and has a slightly larger diameter. Judged by the magnitude of its leakage-current surges at working voltage it is almost as good as P.7, and is also not much affected by large quantities of salt or by upward air currents. In the over-voltage tests it did not behave so well as P.7, and in one test the circuit-breaker tripped at a little more than twice working voltage.

P.5 and P.6 are two large insulators very similar in shape and size, and their behaviour during the tests was very similar. In the least severe test they behaved almost as well as P.8, but with the larger quantity of salt and with upward air currents the deposits had more effect on them, and leakage currents of 4 to 5 milliamp. were observed. In the over-voltage tests, voltages of 2 to 3 times working voltage could be applied to these insulators.

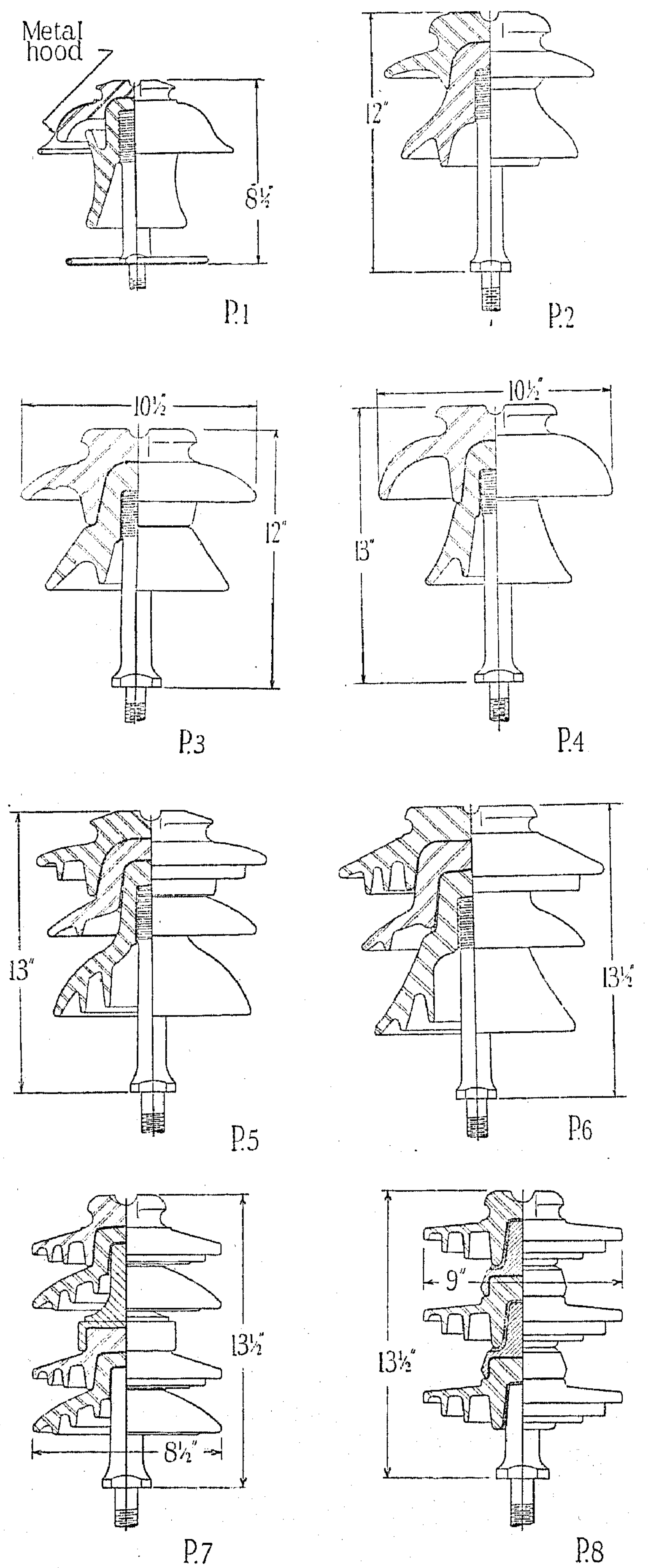


Fig. 6.—Pin insulators.

P.4 is a smaller insulator, but it behaved well provided it was not subjected to upward air currents. In the test with the deposit formed from 1 000 cm³ of solution its maximum leakage current was 3 milliamp., which is smaller than those recorded for P.5 and P.6. When upward currents of air were imitated, however, the deposit was much more severe and the leakage current surged up to 16 milliamp. The good behaviour of this insulator in horizontal wind is probably due to the sheltered regions provided by the deep recess round the pin and the deeply overhanging upper shed. Upward currents of air can, however, carry the deposit into these regions. The maximum voltage which could be applied to the insulator was from $1\frac{1}{2}$ to 2 times the working voltage; it was lower than with P.5, P.6, P.7, and P.8, probably because the insulator is smaller.

Table 6

Summary of Salt Tests on Pin Insulators

Insulator type	Maximum leakage-current surge at working voltage			Voltage at which leakage current exceeds 50 mA (circuit-breaker trips)		
	Test (*a*)	Test (*b*)	Test (*c*)	Test (*a*)	Test (*b*)	Test (*c*)
	mA	mA	mA	kV	kV	kV
P.1	0·35	0·4	2	40	30	22
P.2	4·0	35	30	25	25	27
P.3	4·0	10	25	35	25	25
P.4	1·8	3	16	40	30	35
P.5	1·9	4·5	3	60	50	45
P.6	2·0	4·5	5	50	50	55
P.7	1·35	1·8	2	80	55	70
P.8	1·8	1·8	2·9	65	45	65

Test (*a*). 250 cm³ of salt solution sprayed in 10 to 15 minutes, no "nodding," insulator vertical.
Test (*b*). 1 000 cm³ of salt solution sprayed in 10 to 15 minutes, no "nodding," insulator vertical.
Test (*c*). 250 cm³ of salt solution sprayed in 10 to 15 minutes, insulator "nodded" through 90° for 2 minutes, vertical during rest of test.

P.3 behaved badly; even with the least severe deposit its leakage current surged up to 4 milliamp., and the maximum voltage which could be applied to it was less than twice the working voltage. Its behaviour with deposits formed by imitating upward air currents was very bad, and surges up to 25 milliamp. were observed which would have been larger and might have led to flash-over if the impedance of the testing transformer had been smaller. The maximum voltage which could be applied was only 25 kV, i.e. 5 kV above the working voltage.

P.2 also behaved very badly. In the least severe test its leakage current surged to 4 milliamp., and the maximum voltage which could be applied to it was only 25 kV. In the more severe tests, surges of 30 and 35 milliamp. were observed, and in one test the maximum voltage which could be applied was only 22 kV. The deposit formed with upward air currents using 250 cm^3 of salt solution was not so severe as that formed from 1 000 cm^3 of solution in a horizontal wind. This is probably because the sheds are not deeply recessed or overhung, and even a horizontal wind could carry the deposit on to most of the under-surfaces of the porcelain.

Conclusions

The performance of the insulators in these tests agrees well with their performance in practice as far as this is known. From the tests it would be concluded that Type P.1 is a good insulator because even under the most severe deposit conditions it showed no signs of complete failure at its working voltage of 11 kV. It is believed that this insulator has given good service in practice. The tests indicate that P.4 is considerably better than P.3, and this has been confirmed by direct comparison in service. P.5 is claimed to have behaved well under salt deposits, but no direct comparison is available between it and other types. The tests indicate that it is slightly better than P.4. Types P.6, P.7, and P.8, which also behaved well in the tests, have been advocated as good anti-deposit insulators for severe salt conditions.*

It has been stated that the performance of an insulator under salt deposits depends on its surface-resistance coefficient, and the tests confirm this in general. The effects of other factors, such as shape and size, are also apparent, however. For example, the deeply overhung upper shed and the deep recess round the pin of P.4 give it improved performance in horizontal wind, and in general increased size gives better performance in the over-voltage tests. P.7 and P.8 have practically the same surface-resistance coefficient, yet P.7 behaved better in the tests. This may be due to the fact that P.7 has four sheds, which would probably tend to give a better voltage distribution under deposit conditions than the three sheds of P.8.

These points give support to the results of the tests performed in the laboratory, and indicate that such tests can be used to compare the performance of insulators under salt-deposit conditions. The least severe test enables the two worst insulators to be picked out; the more severe tests show the difference in their behaviour more clearly and must be used for differentiating between the better insulators. Moreover, the two more severe tests correspond approximately to fairly severe conditions which might be met in practice. To correspond to extreme natural conditions a more severe test might be used, and would probably show the differences between the better insulators more clearly than the present tests have done.

Further Work

The work is now being continued under the auspices of the British Electrical and Allied Industries Research Association. Improvements indicated by the present work as being desirable have been incorporated, and are as follows:—

(1) A closed-circuit wind-tunnel is being used, and wind velocities up to 70 m.p.h. have been obtained.

(2) The high voltage is applied by a 33-kV single-phase power transformer having a full-load output of 1·6 amp. This will enable the heaviest leakage currents to be supplied without appreciable drop in voltage.

(3) The technique for artificial dew-formation is being further investigated.

(4) Measurements are being made of the degree of radio interference produced by the various insulator types while under deposit tests.

* See Bibliography, (8).

PART II

INVESTIGATION OF POSSIBILITY OF PROTECTING INSULATOR SURFACES FROM DEPOSIT

General

One important application of the technique devised by the authors should be to the development and testing of new insulator designs to withstand deposit conditions. In this section an account will be given of work done in an attempt to develop such a new design.

There are, at present, two classes of insulator design for dealing with the problem of deposits. The first possesses open exposed surfaces, which, although they are fully exposed to the deposits, are easily cleaned by natural phenomena such as wind and rain. The second class of insulators possesses long, deeply recessed, well-protected surfaces on which it is difficult for the deposit to settle, but from which it is even more difficult for it to be removed by wind and rain.

The considerable success of the first type in inland districts of Britain is probably due to the slow rate of formation of industrial deposits and the regular and frequent occurrence of rain. While these conditions prevail the state of the deposit never departs much from the equilibrium condition, which, in the case of well-exposed surfaces, is one of comparative cleanliness. Near the sea coast, however, insulators are subjected to winds carrying salt spray which may form a dangerous deposit in a few hours. In this case there is considerable probability of dew or mist occurring after the formation of the deposit and before it has been removed by rain. Insulators intended for use near the sea, therefore, must be based on the second class of design, and the designer must aim at making an insulator with surfaces so well protected that deposit cannot settle on them at all. The design about to be described is an attempt to realize this aim.

The basic principle of the design is the provision of an insulating surface which is almost completely enclosed. The only connection between this enclosed surface and the outside air is through a long metal cylinder concentric with the insulator pin. By giving this cylinder suitable proportions the enclosed surface can be protected to such an extent that solid matter carried in suspension in the outside air cannot be deposited on it. Should the unprotected external part of the insulator surface fail completely owing to a deposit on it, then the line voltage will be applied to the metal cylinder.

This is insulated from earth by the internal protected surface and by the air space between it and the pin. Both of these can be designed to provide sufficient insulation against the full line voltage with a factor of safety to give protection against switching surges or small surges induced in the line by lightning.

The principle may be applied either to pin-type or to cap-and-pin-type insulators, but in the tests about to be described pin-type insulators were used because standard pin insulators lend themselves readily to conversion by the addition of the cylinder.

The first tests were made on an 11-kV insulator modified as shown in Fig. 7. The protected surface had

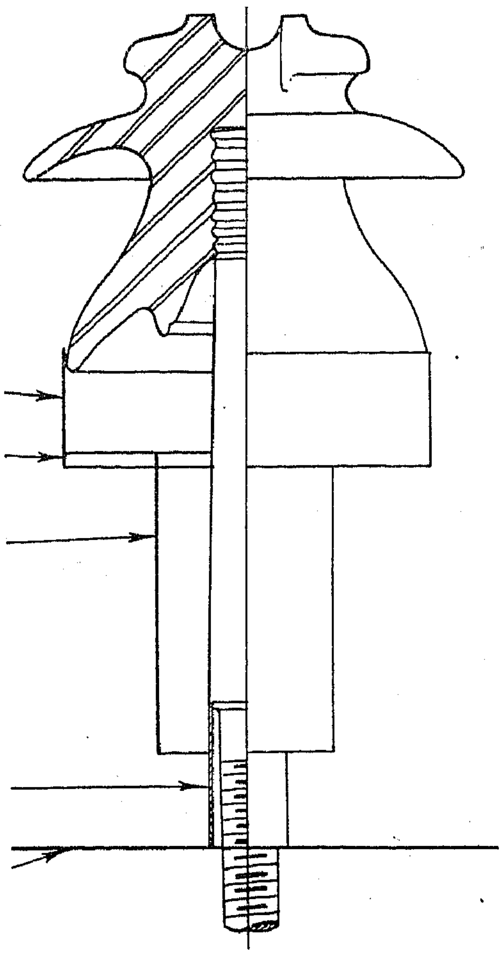


Fig. 7
Scale: $\frac{1}{4}$ full size.

a flashover distance of 3 in. and should have a flashover voltage of about 30 kV. The air-gap between the $1\frac{1}{4}$-in. diameter pin and the $2\frac{3}{4}$-in. diameter cylinder, is in parallel with the protected surface. The gap has a calculated breakdown voltage of 34 kV, but, owing to edge effects, breakdown actually occurred on test at only 17 kV. This insulator was used to investigate how effective the arrangement was in preventing wind-borne deposit from reaching the protected surface. For electrical tests a 33-kV insulator (shown in Fig. 10) was designed.

Protective Action of Cylinder against Wind-borne Deposit

The insulator as shown in Fig. 7 (except that the metal disc at the bottom of the pin had not yet been incorporated) was supported at various angles in front of the open-jet type of wind-tunnel described in Part I, and subjected to wind carrying copper-sulphate spray. Several tests were made for each angle of inclination of the insulator, and 200 cm^3 of solution were atomized for each test at a rate of about 20 cm^3 per minute. The cylinder was polished with emery paper before each test, and, since it was made of iron, a brown deposit of metallic copper was left wherever it became wetted by the copper-sulphate spray. The extent to which the deposit penetrated was thus easily seen immediately after the conclusion of the test.

It was found that a deposit was formed on the inside of the cylinder on the side remote from that facing the wind. This deposit was roughly triangular in shape, with its widest part at the bottom edge of the cylinder, and was divided into two by a clean strip running vertically up its centre where the pin had prevented the spray from reaching the cylinder. At the top end of the triangle the deposit was lighter and composed of smaller particles, and the boundary between it and the clean surface was somewhat indefinite, but the maximum height to which the deposit had penetrated could be determined to within about 0·1 in.

The extent of the penetration of the deposit into the cylinder is shown graphically in Fig. 8, in which the lower graph shows the maximum height at which deposit could be seen and the upper one the corresponding angle (θ) subtended at the leading edge of the cylinder. As the diameter of the cylinder is 2·75 in. this angle is given by

$$\tan\theta = \frac{h}{2\cdot 75}$$

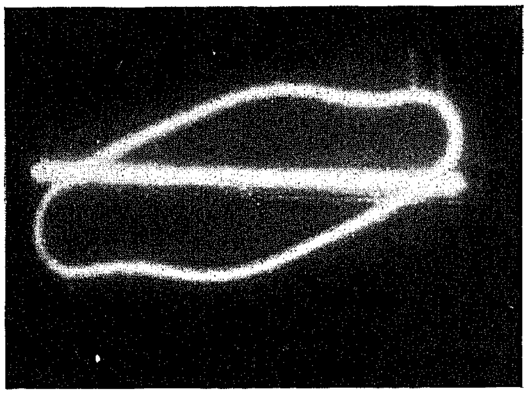
where h is the maximum height of the deposit in inches. From Fig. 8 it can be seen that when the insulator was vertical the deposit was carried by a horizontal wind to a height of just over 1 in., rising inside the cylinder at an angle of about 20°. When the insulator was inclined in order to imitate upward air currents, the height of the deposit increased. When the inclination exceeded about 50°, deposit was carried right through the cylinder on to the internal surface of the insulator. The angle θ subtended by the deposit also increases as the angle ϕ, at which the insulator is inclined, is increased, but the difference between these two angles gets less. Thus when the insulator is vertical and $\phi = 0$, the value of θ is 22°; and the deposit, on passing the edge of the cylinder, appears to be deflected upward through an angle of 22°. When $\phi = 40°$, however, θ is 45° to 50°, and the deposit appears to be deflected through only 5° to 10°.

Effect of Wind Speed

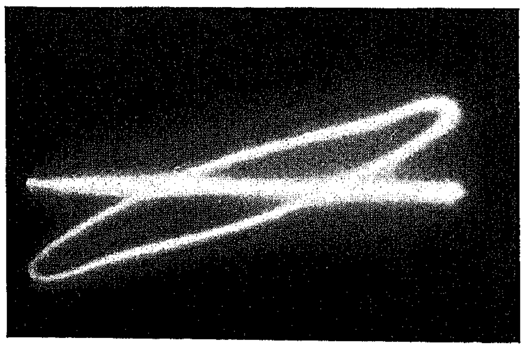
The tests were conducted with wind speeds of 10, 20, and 30 m.p.h., and Fig. 8 shows that the height to which the deposit penetrated was less for lower wind speeds. The effect is, however, not large, since a reduction of wind speed from 30 to 10 m.p.h. only reduces the maximum height of the deposit by about 15 %.

Protective Effect of Disc Attached to Cross-arm

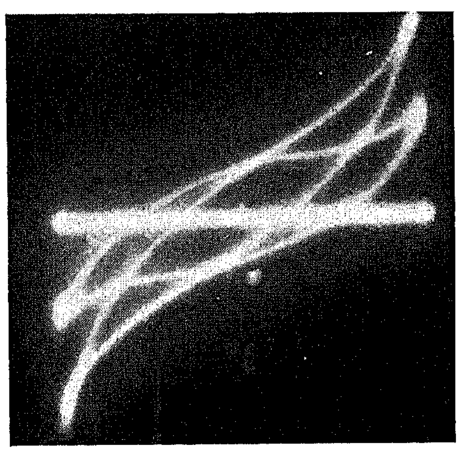
The graphs of Fig. 8 refer to the insulator illustrated in Fig. 7 before the metal disc at the bottom of the pin shown there was added. While the cylinder alone effectively prevents deposit being carried on to the internal



No. 1.
0·15 mA



No. 2.
0·4 mA

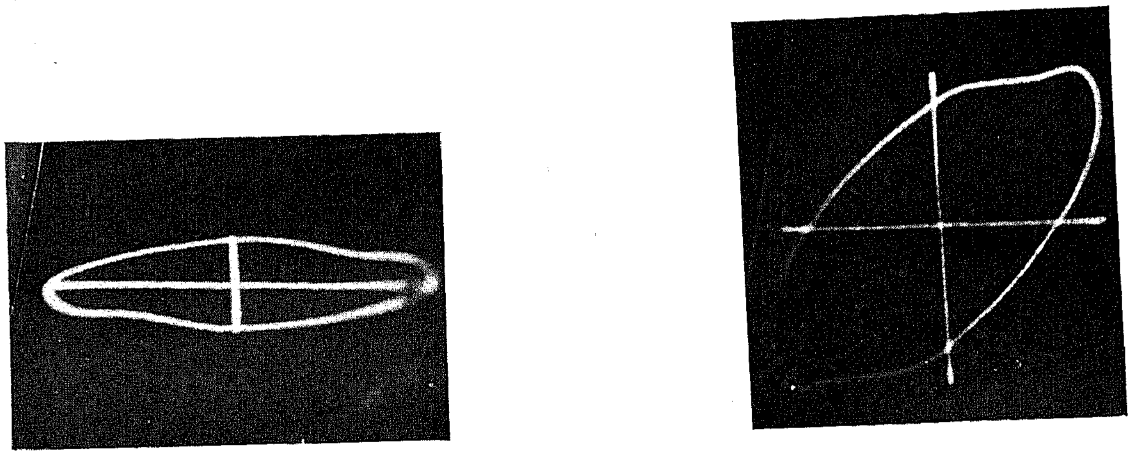


No. 3.
0·5 to 0·9 mA

No. 4.
0·7 to 1·5 mA

Fig. 5.—Oscillograms showing leakage current of insulator P.2 during dew test.

Plate 2



Dry

Under dew

Fig. 11.—Leakage-current oscillograms for Type P.9 insulator.
At working voltage, 20 kV.

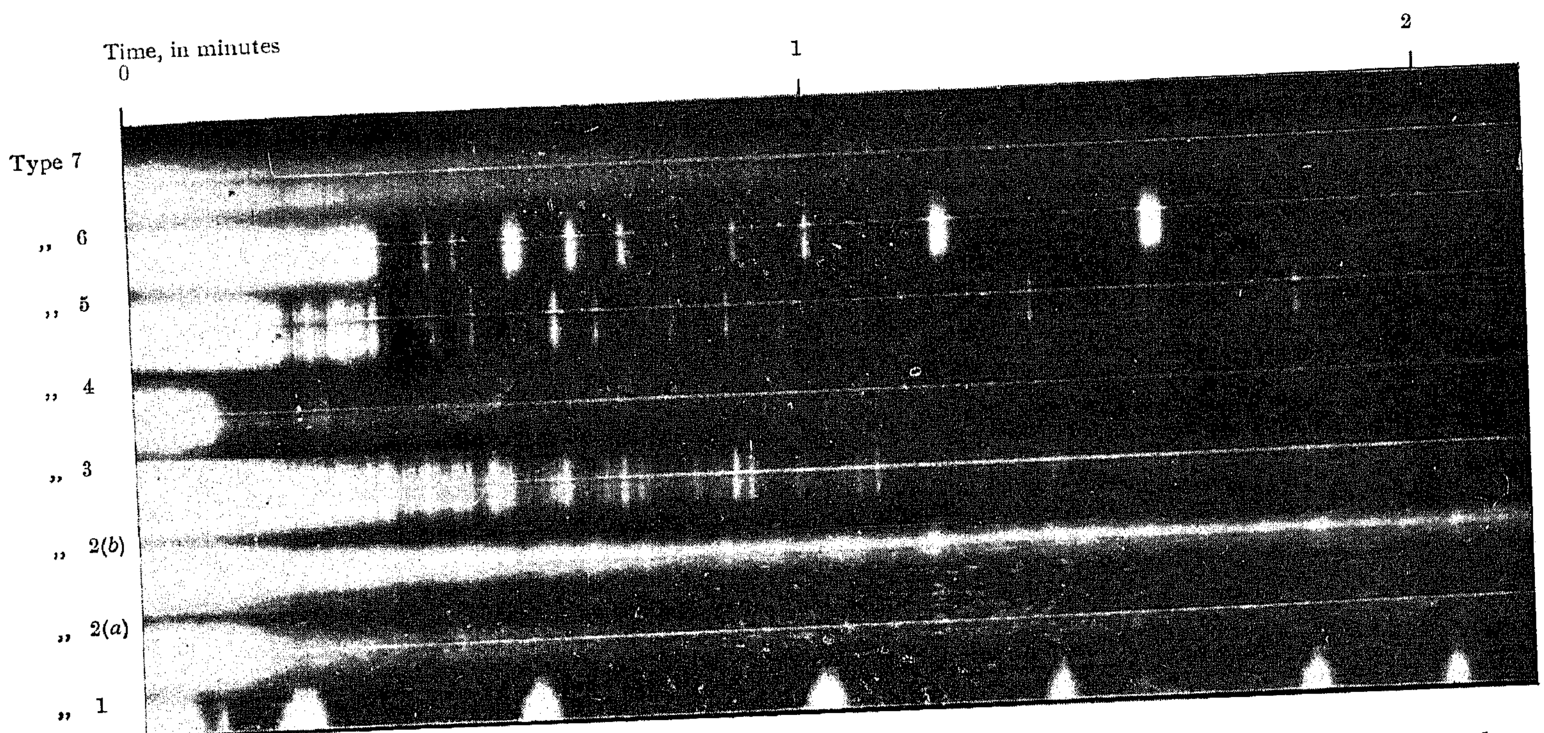


Fig. 17.—Leakage currents, during fog, of insulator strings given in Table 7. (Obtained by recorder shown in Fig 16.)

surface of the insulator by a horizontal wind or one blowing upward at an angle of less than 50°, it does permit deposit to enter if the inclination is greater than this. The increased protection due to the addition of the disc can be seen by comparing the graph of Fig. 9 with the lower one of Fig. 8. It will be seen that, at any given inclination, the deposit has not penetrated so far, and that a sudden cut-off occurs at an inclination of about 45°. For greater inclinations no deposit whatever is carried into the cylinder. With this disc fitted, therefore, deposit cannot be blown into the insulator by wind blowing at any inclination. Moreover, the maximum height to which deposit can be carried by any

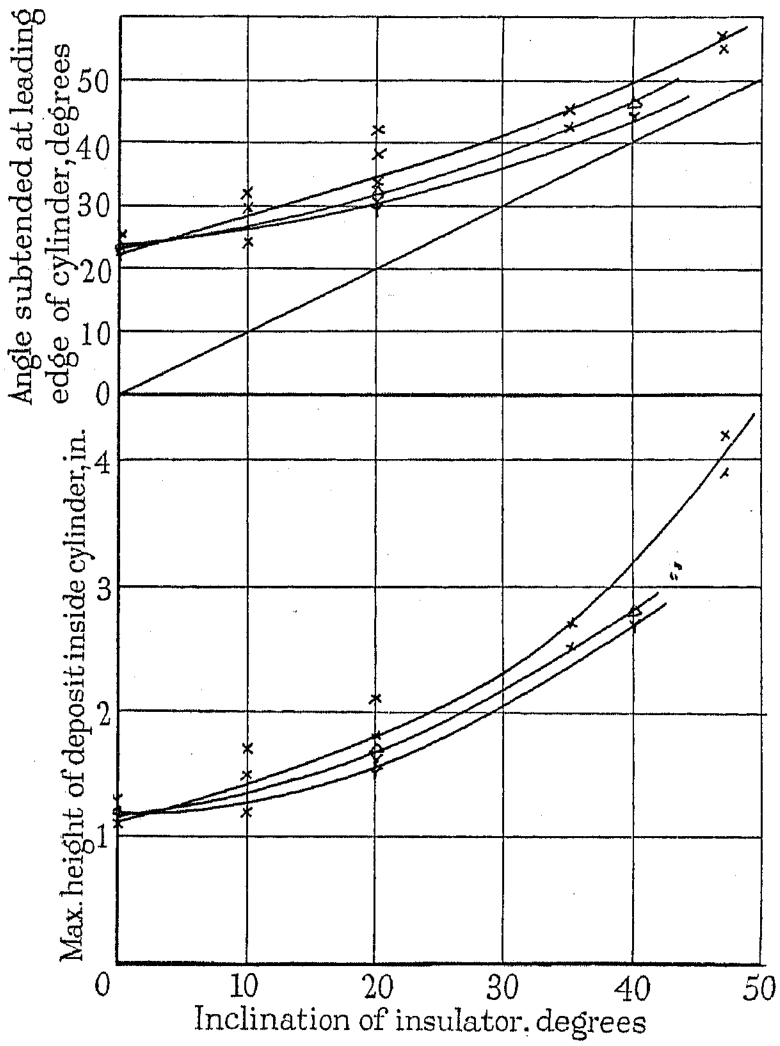


Fig. 8.—Maximum height of deposit inside cylinder (h), and elevation above front edge of cylinder (θ).
—×———×— 30 m.p.h. wind.
—Δ———Δ— 20 m.p.h. wind.
—Y———Y— 10 m.p.h. wind.

wind is about 1·5 in., and the cylinder could therefore be made only 2 in. long and still be effective.

As a line drawn from the edge of the disc to the bottom of the cylinder is inclined at 30° to the horizontal, and wind blowing upward at an inclination of 40° still carried deposit into the cylinder, it appears that there is a deflection of the wind by the disc. A similar deflection was found to occur at the edge of the cylinder, the deposit being carried higher than was expected. These deflections, each amounting to about 10°, must be allowed for when designing this type of insulator, the disc being made of larger diameter and the cylinder being made longer than would be necessary if the deposit were carried in straight lines.

Design Suitable for 33 kV

After the above tests had shown the protective effect of a suitable arrangement of cylinder and disc, it was decided to make a design suitable for 33 kV, since most

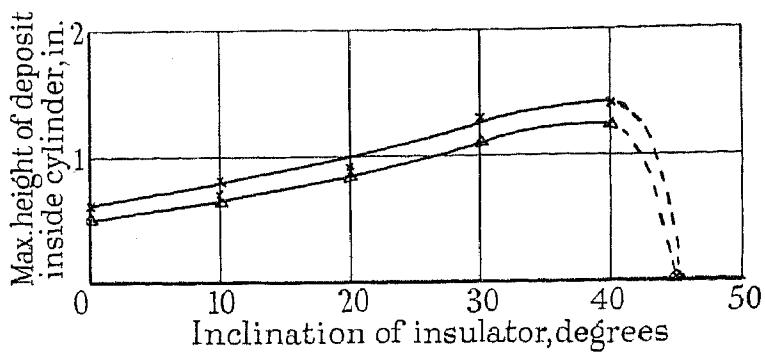


Fig. 9.—Maximum height of deposit inside cylinder (after fitting 8-in. disc 2 in. below cylinder).

of the pin insulators available for tests under salt deposits were 33-kV types.

A Type P.3 (Fig. 6) porcelain was used. The flashover distance along the porcelain from the outer edge of the bottom shed to the pin was 5 in., and the flashover voltage should therefore be approximately 50 kV. This surface alone if properly protected should therefore withstand the working voltage (20 kV to earth) of a 33-kV insulator with a factor of safety which can be considered adequate for deposit conditions. The modified insulator

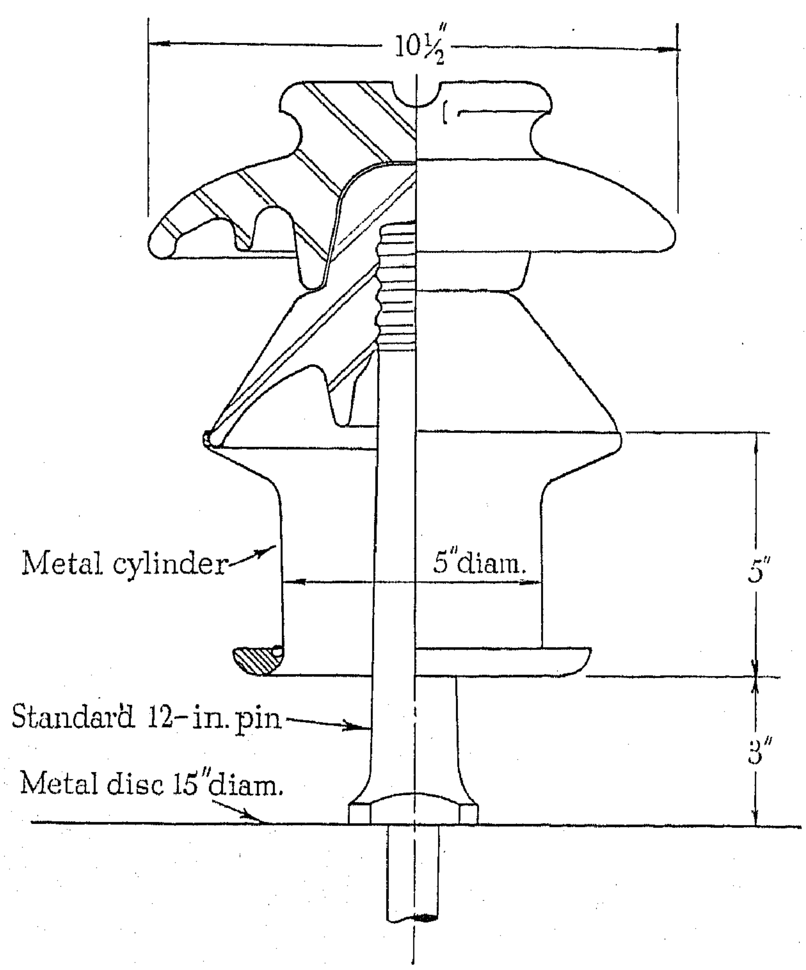


Fig. 10.—P.9 insulator.

is shown in Fig. 10. The diameter of the external cylinder was 5 in., and of the pin was $1\frac{1}{2}$ in. At the top the cylinder opened out to a diameter of 8·3 in. and was cemented to the lower shed of the porcelain. The

disc at the bottom of the pin was made 15 in. in diameter and was 3 in. below the bottom of the cylinder. With this arrangement, if voltage was applied directly between cylinder and pin, flashover occurred at 60 kV. The dry flashover voltage of the complete insulator was 116 kV. The insulator was designated P.9.

The first tests on the Type P.9 insulator were to find how far deposit could be carried into the cylinder by winds blowing at various inclinations. For these tests the cylinder was painted black and the deposit, which was formed from sea salt, showed up as white crystals when dried after the test. The cylinder was wiped clean and polished with a dry cloth before the commencement of each test.

With a horizontal wind, a very fine deposit was formed which reached to a height of about 1 in. As the inclination of the insulator in imitation of upward air currents was increased, the height of the deposit increased until, at an inclination of 40°, a few large particles could be seen at a height of 2·7 in. At greater inclinations than this no deposit at all could be seen inside the cylinder. As the length of the cylinder is 4 in., the design of the insulator is satisfactory from this point of view and the cylinder and disc prevent deposit being carried on to the internal surface of the porcelain by wind blowing at any inclination.

Type P.9 Insulator: Its Electrical Performance under Deposit Tests

The behaviour of the Type P.9 insulator when subjected to the tests of three different severities developed in Part I was always exactly the same. With an applied voltage of 20 kV the leakage current rose slowly during the formation of dew from its original value of about 0·2 milliamp. to a value of about 0·6 milliamp. After this a very faint discharge became audible and the leakage current varied slowly over a range of about 0·02 milliamp. The oscillogram of leakage current on a voltage base remained a plain loop throughout the test and increased in size as the current increased (Fig. 11, Plate 2). It remained perfectly stable and gave no indication of discharges on the insulator.

The behaviour of the insulator was similar when tested in dew without any salt deposit. It was also similar when tested in dew after a very severe salt deposit had been formed on it during a series of tests in which a total of 1 500 cm³ of salt solution was atomized and winds blowing upward at various angles had been imitated. The deposit so formed would certainly have had a considerable effect on any of the other pin insulators the tests on which are described in Part I, yet the Type P.9 insulator behaved during dew periods exactly as when it had no deposit.

When the voltage was raised above working voltage, breakdown eventually occurred at 40 kV by flashover of the internal surface. At breakdown there was a heavy leakage current over the rest of the insulator surface on which a heavy deposit of dew had been able to form owing to the low leakage current prior to breakdown.

During the over-voltage tests, the leakage current and its wave-form were measured at voltages up to 35 kV. At 20 kV the current during one test varied between 0·56 and 0·59 milliamp., and the discharge was just audible. At 25 kV the leakage current became 0·72 milliamp. and the discharge became slightly louder. The oscillogram remained a loop and was not distorted, but some very short-duration peaks occurred in the current at about the instant of maximum voltage; the oscillogram appeared very similar to oscillogram No. 1 (Fig. 5). After 2 minutes these peaks had disappeared and the oscillogram was again a plain loop, the discharge had become quieter again, and the leakage current had fallen and was varying between 0·65 and 0·70 milliamp. At 30 kV the leakage current rose to 0·82 milliamp. After a few minutes the current was varying between 0·77 and 0·8 milliamp., the discharge was considerably

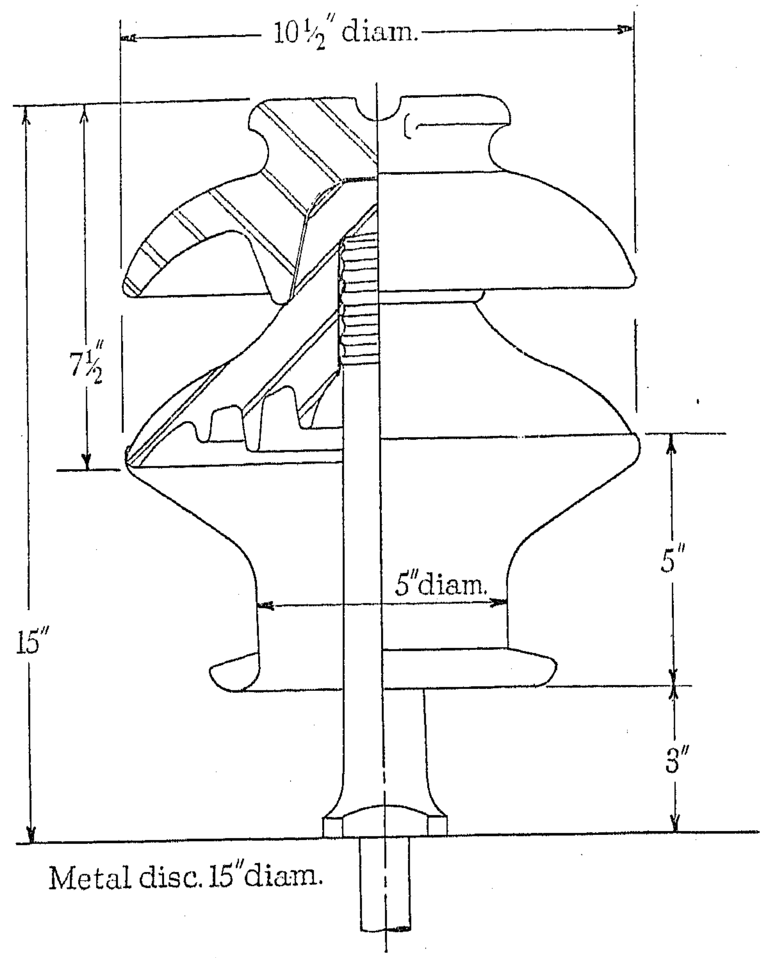


Fig. 12.—33-kV concentric-cylinder pin insulator.

louder than it had been at 20 kV, and the oscillogram, while remaining undistorted, showed short-duration current peaks near the points of maximum voltage. At 35 kV the leakage current rose to 0·9 milliamp., faint sparks could be heard inside the insulator, and the peaks on the oscillogram became larger. The measuring instruments were then disconnected and the voltage raised slowly until flashover occurred at 39 kV.

During the dew test the surface resistance of the protected part falls. If 20 kV was applied directly between cylinder and pin, a leakage current of 0·4 milliamp. was recorded before dew formed, and this rose to 0·6 mA after dew formation. To determine to what extent the internal surface was effectively protected from dew formation, the insulator, with the protecting cylinder and disc removed, was subjected to a deposit formed by

atomizing 250 cm^3 of salt solution and imitating upward air currents. The cylinder and disc were fitted and the insulator subjected to dew. Its behaviour, with 20 kV applied, was little worse than it would have been with no salt deposit on the internal surface. The leakage current without the protection would have surged between 10 and 20 milliamp., but now it rose to 0·75 milliamp. only and varied between this and 0·73 milliamp. On raising the voltage, flashover occurred at 35 kV. This proves that the formation of dew on the internal surface is in fact almost entirely prevented by the cylinder and disc. The relative humidity of the air inside the insulator was probably 100 % during the dew test. No deposition of dew occurs, however, since there is no effect tending to lower the surface temperature of the insulator, which is maintained slightly above the dew point by the heating effect of a very small leakage current.

Surges of large magnitude due to lightning are unlikely to occur during conditions of dew, mist, etc., but surges caused by switching may occur. In order to render the insulator safer from these, the breakdown voltage of the internal surface should be increased. Fig. 12 shows a suggested design for a pin insulator similar to Type P.9 but with a longer protected surface. It is hoped that the breakdown voltage of the internal surface of this insulator will not be reduced below 60 kV, even in mist. Several porcelain insulators have been made to this design, but were not completed in time to be tested.

Industrial Deposits

A small glass insulator incorporating the protective cylinder was exposed to industrial deposits side by side with an unprotected insulator. After 18 months its protected surface was still clean, while the similar part of the unprotected insulator was very dirty. It appears, therefore, that the protective features are of use against industrial as well as saline deposits.

Conclusions

The tests show that an arrangement embodying a cylinder concentric with the pin and a disc attached to the pin just above the cross-arm affords complete protection to the internal surface of an insulator against deposit carried by wind at any inclination. Protection against deposit carried by horizontal winds and by winds of small inclination can be given by the cylinder alone, and it has been found that the cylinder alone also gives almost complete protection against industrial deposits. In the electrical tests it was found that the arrangement of cylinder and disc also protected the internal surface of the insulator against dew; so that the performance of the insulator during the dew test, even with a deposit on its internal surface, was very much better than that of any of the orthodox designs.

The fact that when the insulator was tested with the most severe salt deposits there were no discharges which could be seen or recorded by the cathode-ray oscillograph, should mean that the insulator will not cause radio interference.

PART III

FORMATION OF INDUSTRIAL DEPOSITS UNDER NATURAL CONDITIONS

Testing Equipment

The laboratory is situated in East London, where considerable atmospheric pollution occurs. A number of strings of suspension insulators were hung from a gantry on the roof of the laboratory to enable the authors to study the formation of industrial deposits on them. Fig. 13 shows the position of the gantry on the roof. Only one high building which might shield the insulators is near the gantry. To the east and west the gantry is fully exposed, and this is important since the prevailing

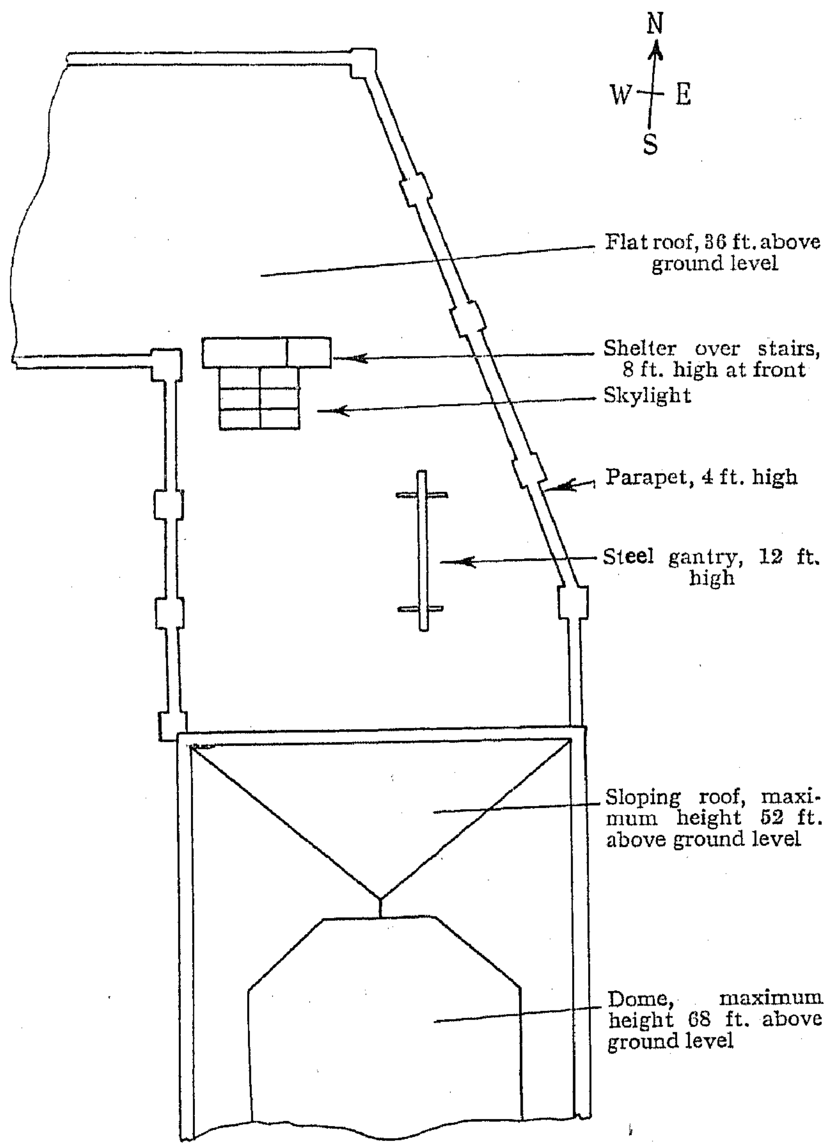


Fig. 13.—Outdoor testing area.
Scale: 1 in. to 36 ft.

wind is from the west or south-west. Moreover, to the west is a chimney rising to about the same height as the gantry, and which frequently emits large quantities of black smoke. To the east, separated by about 800 yd. of flat open ground, are more chimney stacks and a busy railway siding. Thus the gantry is not shielded appreciably except to the south, and is quite exposed in the direction of the prevailing wind and of the main sources of pollution in the immediate neighbourhood.

A roof bushing enables the insulators to be connected to the 150-kV high-voltage transformer used in the salt-deposit tests. Lightly-insulated leads for measuring

purposes are taken through steel tubes passing through the roof.

The deposits must be considered to have formed on insulators without voltage applied, since the voltage was only switched on for short periods while the measurements were being made. It is controversial what effect the application of voltage to the insulators has on the formation of the deposit; some authorities affirm that there is none, while others consider that there is a small effect.*

Insulators Tested

The tests were made on cap-and-pin type insulators made into strings of about the same length as the normal suspension strings used on the 132-kV sections of the British grid. The representative selection of insulator types shown in Fig. 14 was tested. Type 1 represents the normal type of cap-and-pin insulator, and most of the British grid is insulated with units of this or very similar design. The other types are special designs intended for use under deposit conditions. Types 2(*b*), 4, and 5 have been used extensively in Britain. Type 7, designed primarily as a "puncture proof" insulator, is also claimed to behave well under deposit conditions.

Table 7

SUSPENSION-INSULATOR STRINGS

Type	Number of units in string	Total length per string
		in.
1	10	52·5
2(*a*)	9	47·25
2(*b*)	9	49·5
3	9	51·75
4	8	50
5†	10	50
6‡	10	50
7	4	54

† Some of these units were different from those shown in Fig. 14; they were designed for a higher mechanical strength and had larger caps.
‡ Some of these units were different from those shown in Fig. 14; instead of the triple spiral they had a single spiral of shorter pitch.

After preliminary tests all the insulators were cleaned and hung up in strings, as shown in Table 7. Another string contained Types 8, 9, 10, 11, and 12, and a Type 4 unit inverted.

Visual Observation of the Formation of Deposits

After the insulators had been exposed for 1 day, a deposit of coarse granular material could be seen on the top surfaces. This could be wiped off with a dry finger; it felt soft, left a black mark on the finger, and was, no doubt, mainly soot. No deposit was visible on under-surfaces, but after about 4 days a very faint black mark was left on the finger if it was wiped over these under-surfaces. The deposits on the top surfaces showed no steady growth but fluctuated with various weather conditions. For example, the surfaces were much cleaner just after rain than after a long dry period. On the under-surfaces the deposit grew more steadily, had a finer grain, and was more closely adherent to the porcelain. It showed at first as a slight dulling of the glazed surface and was only apparent by contrast with a clean surface formed by wiping part of it away. Appreciable deposit on the under-surfaces first became visible after about 3 weeks and, in contrast with that on the top surfaces, at once

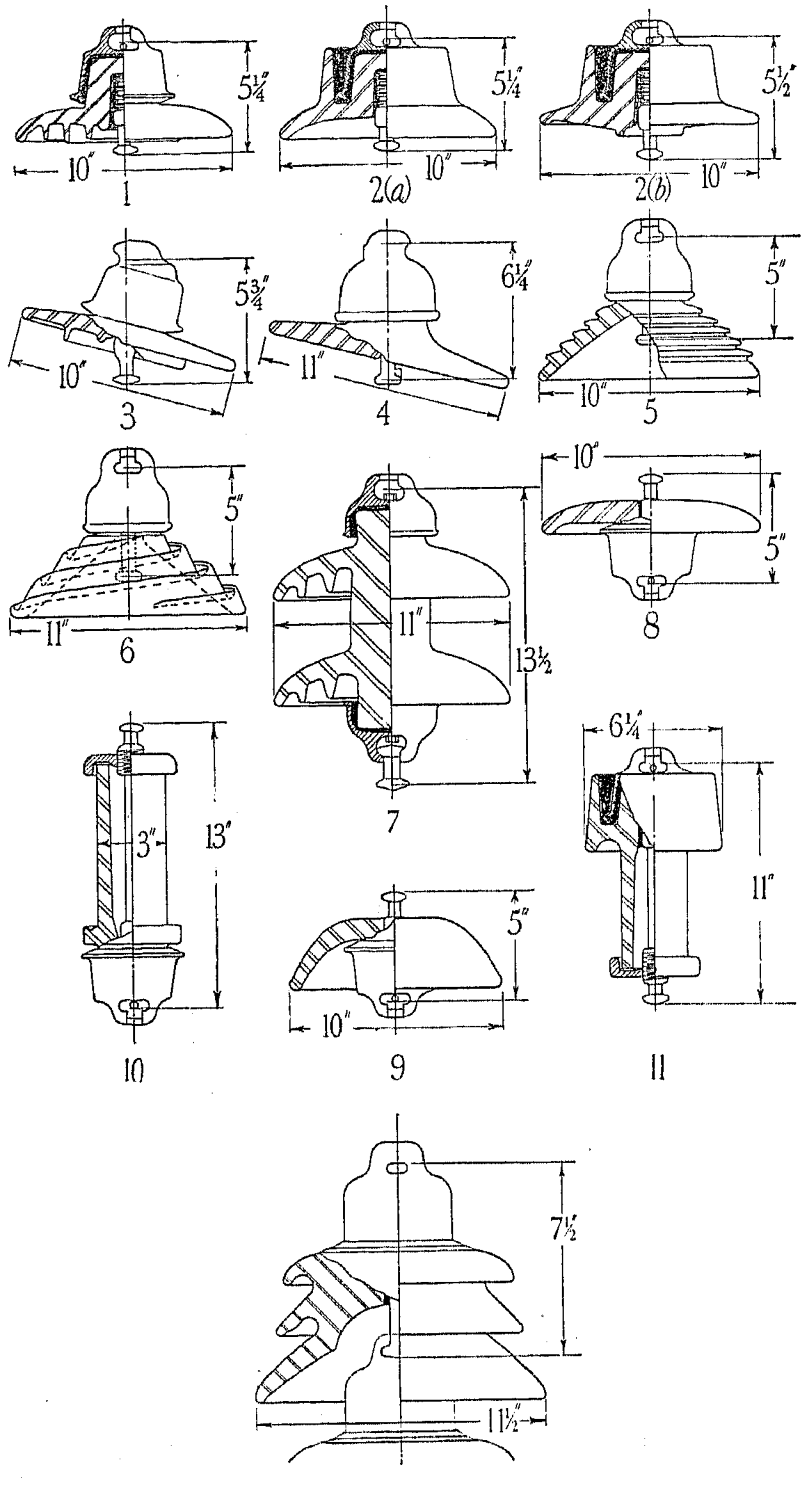


Fig. 14.—Suspension insulators.

showed a tendency to collect in certain places and not in others. For most types the deposit seemed to collect most rapidly in the vicinity of the pin. Thus in the cavities round the pins of Types 1, 2(*b*), and 3, the deposit collected most rapidly, while on the insides of Types 5, 6, and 9 the deposit collected first near the lower edges but was soon visible right up to the pins, where it later became thickest. Other positions where accumulations of deposit occurred were: inside the drip-

* See Bibliography, (3), (8), and (11).

beads at the outer edge underneath Type 2(*b*) units, in the bottom of the grooves of Type 6 units, especially those with a single spiral, and on the sides of the ribs of Type 5 units. The vertical cylindrical parts of Types 2(*a*), 2(*b*), 7, 10, and 11 remained very clean, as did also the edges of top surfaces. On Types 5 and 12 the edges of the ribs and sheds were all clean, but the tops of the sheds where they were overhung were rather dirtier than the top surfaces of other units.

After about 3 months the deposits were in general as heavy on the under-surfaces as on the top surfaces. In well-protected positions, such as the channels between the ribs of Type 1 units, the deposit was still not as thick as that, for example, on the sides of the ribs but could be easily observed by contrast with a clean surface. Marked accumulations of deposit could be observed in cavities round the pins, inside the drip-beads of Type 2(*b*), and on the internal surfaces of Types 5, 6, and 9. On comparatively flat surfaces such as the tops of most types, the bottoms of Types 2(*a*) and 4, and the plain cylindrical surfaces of Types 2(*a*), 2(*b*), 7, 10, and 11, the deposit was approximately uniform.

After 11 months (April, 1936, to March, 1937) the deposit on all top surfaces was about the same as it had been after a few weeks. The vertical cylindrical surfaces of Types 2(*a*), 2(*b*), 7, 10, and 11 were also about the same as at the beginning of the test and were slightly cleaner than horizontal top surfaces. Plain under-surfaces such as those of Types 2(*a*), 2(*b*), and 4 had about the same density of deposit as horizontal upper surfaces. Heavier deposits were found on insulators with ribs or with enclosed surfaces, and these deposits were heaviest at small diameters, i.e. near the pins. Inside bell-shaped units, such as Types 5, 6, 9, and 12, and near the pins of Types 1, 2(*b*), and 3, the deposit reached a thickness of about $\frac{1}{32}$ in. and when scraped off and weighed showed 1·6 milligrammes per cm^2 of surface. On most strings the under-surfaces of the bottom units were considerably cleaner than those of the other units.

The deposit could easily be wiped off the insulators, and where it was thick was light and powdery when dry. The deposit was easily wetted and was not oily, but it could not be completely removed by placing the insulator in running water. For example, an insulator was placed under a water tap and a jet of water was allowed to fall on it for 30 minutes. After the insulator had dried, a considerable film of fine black deposit still remained on it.

Plain cylindrical surfaces were not visibly affected by washing under running water, and this shows that on well-exposed surfaces a deposit forms which cannot be removed by the action of water. Whether this deposit reaches a final density or whether it continues to grow slowly cannot be judged from the present experiments.

Measurement of Leakage Current of Insulator Strings

The top ends of the insulator strings, which would normally have been earthed, were insulated by an additional unit so that the leakage currents could be taken by cables into the laboratory and there measured.

Eight separate screened leads, consisting of single-core lead-covered cable, were brought from the eight strings of insulators into the laboratory, where, by means of a selector switch, seven of them were connected directly to earth and the eighth was connected to the measuring instruments. Errors due to the current being shunted from the measuring instruments through the capacitance or leakage conductance of the cable were shown to be small, even when the wave-form was distorted.

The circuit diagram of the measuring equipment is shown in Fig. 15. The milliammeter and cathode-ray oscillograph were those described in Part I, dealing with

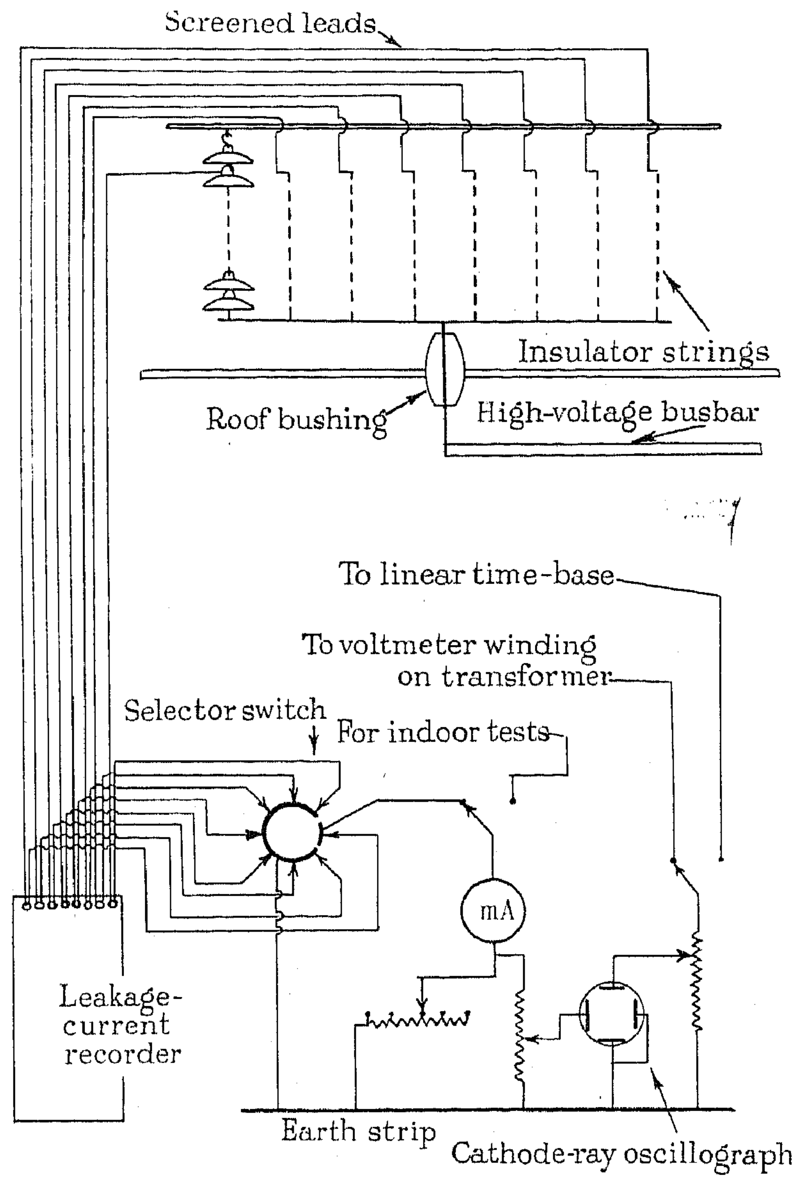


Fig. 15

salt testing. By means of a change-over switch they could be connected either to the lead from the indoor test area or to the leads from the roof area.

Leakage-current Recorder

Since the leakage currents of the eight strings of insulators were measured by means of a single milliammeter and selector switch, readings could be taken in rapid succession but not simultaneously. This was quite satisfactory for steady conditions. In bad weather conditions, however, it was desired to measure the magnitude and frequency of leakage-current surges occurring at random, and this required continuous and, for true comparison, simultaneous readings for all insulators. This was only possible by means of a form of 8-element

recording milliammeter. After preliminary experiments an inexpensive form of recorder was constructed in the form shown in Fig. 16, using eight neon lamps as indicators. The lamps were ordinary small neon lamps for use on 200- to 250-volt circuits, and the electrodes were discs inside circular loops. They were placed in a row behind a metal screen which was parallel to the plane of their electrodes and in which was a straight narrow slit parallel to the plane containing the axes of the electrodes but slightly displaced from it. The lamps were then placed in a light-tight box containing a lens which focused the light passing through the slit on to a slowly moving photographic film.

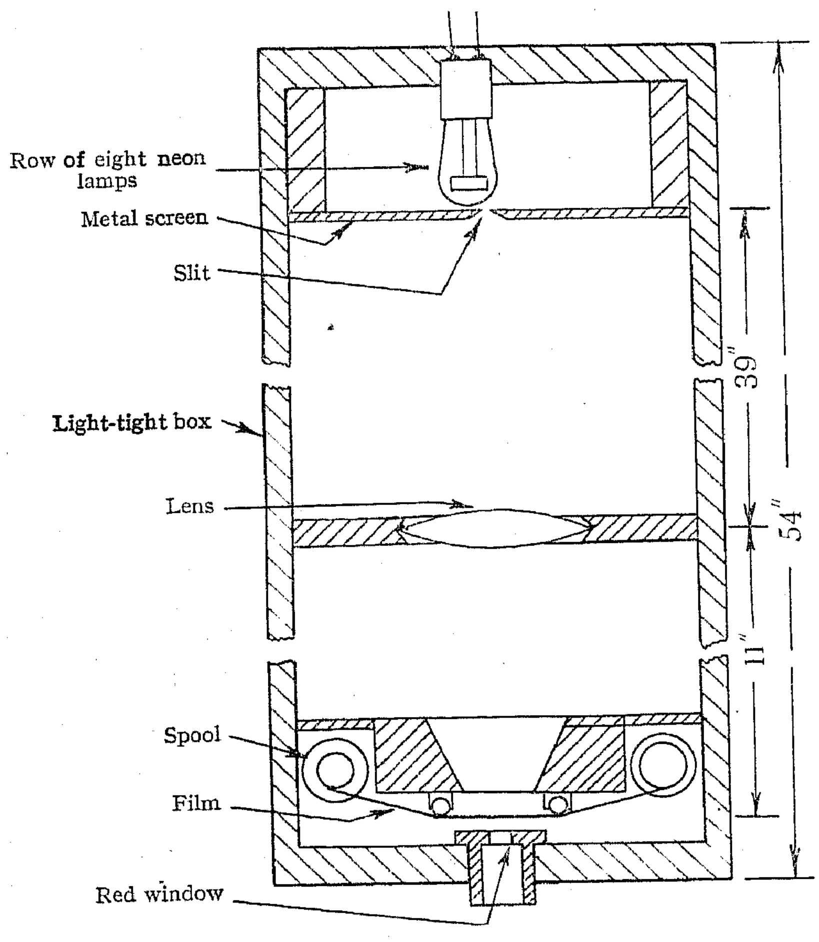


Fig. 16.—Leakage-current recorder.

Each lamp was connected in series with a lead from one insulator string and had a resistor connected across it as a shunt. It was found that when resistors of 500 000 ohms were used the lamps lit brightly enough to affect the photographic film when the leakage current exceeded about 0·5 milliamp. It was not found necessary to remove the stabilizing resistor from the lamps.

Fig. 17 (Plate 2) shows a specimen print made from part of a record obtained during fog. The beginning of the record, which is shown at the left of the print, corresponds to the time at which voltage was first applied to the insulators. The large initial leakage current taken by each insulator caused all the lamps to light brightly, and each trace starts as a wide bright band. As the leakage current diminishes, the traces become narrower and fainter and some disappear almost entirely. (The straight white lines were ruled on to the film in order to show the centre of each record.) Current surges are well shown up, and it is possible to compare their magnitude.

Results

It was thought that measurements of leakage current under fine weather conditions should give an indication of the growth of the deposit on the insulator surface. Accordingly, the leakage current at working voltage of each string of insulators was measured each day. In attempting to interpret the results it was soon realized that it was necessary to correct for relative humidity, since this varied from day to day and had a large effect on the magnitude of the leakage current. Even when this correction was made the records showed no marked difference as between different insulators, although some had collected much more deposit than others. The conclusion reached is that the conductance of the deposit in average good weather conditions is not a measure of the deposit on an insulator. The explanation probably is that the parts of the insulator on which the deposit collects most thickly have a comparatively small resistance, while small areas (such as the edges of ribs and sheds) which remain clean have a much higher resistance and therefore account for practically the whole resistance of the insulator surface. It was therefore the resistance of these parts and its variations which was measured.

The measurements are therefore of no value for comparing the performance of the insulators, but some conclusions can be drawn from the results. Firstly, the well-known washing effect of rain is definitely shown, though this effect is probably limited to small well-exposed parts of the insulators. It was found that when the deposit had collected for some time in dry weather a small amount of rain had a large cleaning effect. After the initial cleaning, however, the effect of more rain was much smaller, showing that, while much of the deposit can be washed off easily, there is underneath a more firmly adherent coating. Secondly, the conductances of the insulators at the end of the test were only slightly greater than those of clean insulators. During the period of the test the conductance had fluctuated about values not much greater than those of the clean insulators. This suggests that, at least on certain parts of an insulator, which are probably the well-exposed parts, the deposit reaches an equilibrium condition, its growth during some periods being balanced by natural cleaning during others. Thirdly, the results show that, on the well-exposed parts, the deposit collects much more rapidly when the humidity is high; during the summer months, when the humidity was usually between 40 % and 70 %, the deposit did not collect at all. As most surfaces become slightly moist if the humidity of the air exceeds about 80 %, the results suggest that the deposit does not adhere to exposed surfaces unless the insulator surface or the deposit itself is moist.

Bad weather conditions which lead to flashover in service are fog, mist, dew, and frost. In the present tests the insulators were outdoors and exposed to natural weather conditions, and the bad-weather tests were therefore limited by the number of occasions that suitable weather conditions occurred at times when measurements were possible.

A summary will now be given of the results of observations made during bad weather conditions (see also Table 8).

Fog and Mist

Fog and mist did not occur very frequently, and when they did occur they often had surprisingly little effect on the insulators. Thus on the 4th November, 1936, a fog developed during the day, beginning as a white mist and becoming thicker. At 11 a.m. the relative humidity reached 82 % and the insulator leakage currents were all steady though above normal, the maximum value being 0·27 milliamp. for the Type 1 insulators. Later, when the mist turned to a dark yellow fog, the relative humidity decreased and so did the leakage currents of all the insulators.

The only bad fog conditions were experienced between the 23rd and the 27th November, and, during these, considerable surging occurred. The Type 1 insulators behaved worst, surges up to 10 milliamp. being observed. The best insulators were Types 2(*a*), 2(*b*), and 4, the leakage currents for which were high and unsteady but did not surge. For Type 7, surges up to 1 milliamp. were observed; and for Types 3, 5, and 6, surges of about 2 milliamp.

Table 8

Maximum Leakage-Current Surges Recorded for Suspension-Insulator Strings Under Bad-Weather Conditions

Insulator type	Leakage current:—			
	During fog	During mist and rain	During rain	During frost
	mA	mA	mA	mA
1	10	10	8	3
2(*a*)	0·5*	2	2	2
2(*b*)	0·5*	2·5	2	1·5
3	2	4	3	2·5
4	0·55*	1·5	1·5	1·2
5	2	7	3	1·5
6	2·5	3	3·5	1·5
7	1	4	1·2	1·5

* No surging, but slightly unsteady leakage current.

The record shown in Fig. 17 (Plate 2) was obtained with the leakage-current recorder during a thick fog on the 25th November, the part printed being a record of the first 2 minutes after applying voltage to the insulators. It will be seen that all the insulators took a large initial leakage current but that a rapid drying-off took place, and the leakage current either became small and ceased to give any record—as is the case with Types 4 and 2(*a*), and later with Type 2(*b*)—or surged and gave an intermittent record, as is seen with the other types. The difference in the performance of the types for which surging took place is shown by the different magnitude of the surges rather than by their different frequency of occurrence. During a period of 5 minutes after the initial heavy currents had ceased, 12 surges were recorded for the Type 1 insulators, 12 for Type 6, and 14 for Type 5. The record for the Type 3 insulators is characterized by a large number of small surges.

During this period of fog, discharges which were bright enough to be seen in daylight occurred on the insulators. On the Type 1 insulators, arcs were seen starting from the pins and passing across the under-surfaces of the porcelain. On Types 3, 5, and 6, heavy sparking occurred near the pins; on Type 4, small surface sparks spread out from the pins; and on Types 2(*a*), 2(*b*), and 7, faint sparks were sometimes seen on the porcelain cylinders.

Rain

During rain, the leakage current of all types was usually unsteady, and towards the end of the tests, when the deposit was thickest, fairly heavy surges were recorded. The Type 1 string was the worst, with surges up to 8 milliamp. and arcing discharges spreading out from the pins. Types 3, 5, and 6 had sparking discharges spreading out from the pins accompanied by leakage-current surges.

On several occasions rain was accompanied by mist, and this constituted for the majority of the insulators the most serious weather which occurred during the tests. (When comparing the performance of insulators in fog with that in mist and rain, however, it must be remembered that the fog occurred earlier in the tests and before the deposit had reached its worst condition.) On the Type 1 string, surges up to 10 milliamp. were recorded during rain accompanied by mist. On Type 5, sparks were seen spreading out from the pins; while on Type 7, sparks passed down the vertical porcelain cylinders. Type 3 also behaved badly, sparks spreading out from the pins and also at times passing between the edges of adjacent discs where they approached one another. (The discs of these insulators were sloped in different directions.)

Frost and Dew

On two occasions when frost or dew appeared likely, the sky being clear and free from clouds, observations on the insulators were continued throughout the night. On neither occasion, however, did frost or dew occur, and all the leakage currents remained normal and steady throughout the night. On one of these occasions heavy frost occurred a few miles out of London, and it was concluded that in all probability the polluted atmosphere, by reducing radiation, prevented the formation of dew in the town itself although the sky was free from clouds.

On two occasions, however, temperatures below freezing point were experienced in the early morning and, although no frost was visible on the insulators, very heavy leakage currents were observed when the voltage was first applied, and when the initial heavy currents had died away surging took place. On the worse of these occasions the temperature was − 0·8° C. and the relative humidity was 88 % (measured by the wet-and-dry bulb whirling hygrometer). Arcing discharges were seen underneath some of the units of the Type 1 string, and surface sparks on the other types.

Leakage-current Wave-form

Oscillograms of the leakage currents during bad weather conditions were very similar to those obtained for pin insulators (see Fig. 5, Plate 1). They showed current surges of various magnitudes occurring at about maximum voltage during each cycle.

Comparison of Insulator Types

In attempting to use these tests in order to judge the relative merits of the various types for service under deposit conditions, several points must be remembered. The insulators were assembled for the final test in April, 1936, and the tests ended in March, 1937, and it was only in the latter half of these 11 months that the deposits were heavy enough to affect the insulators seriously. In measurements made during such a comparatively short period a considerable element of chance is present, and a longer time is necessary in order to avoid false impressions due to unusual effects. Moreover, if the duration of the tests is too short, the results will show which insulators begin to get dirty most rapidly rather than which insulators finally reach the most dangerous condition. Also, none of the insulators reached a dangerous condition since, according to Forrest's work,* surges of 100 milliamp. can occur, and it is such surges which are liable to lead to flashover. In the present tests the maximum surges recorded were only 10 milliamp., and for most of the insulators the maximum surges were only 2 to 5 milliamp.

Comparisons of the different types as judged by various criteria were made in order to see what agreement existed between these. The most definite comparison was that based on the magnitude of the leakage-current surges during fog. This indicated that the performance of the normal insulators (Type 1) was worse than that of the anti-deposit types. Of these, Types 3, 5, and 6 seemed inferior to Types 2(*a*), 2(*b*), 4, and 7. Comparisons based on other criteria, namely the appearance of the deposit, the wave-form of the leakage current, and the magnitude of discharges seen on the insulators, although less definite, are in general agreement with the above classification.

Discharges on Insulator Strings

Several interesting conclusions can be drawn from the discharges observed on the insulators during bad weather. Discharges, both surface sparks and arcs, usually started from the pins and spread outwards over the under-surface of the porcelain. Small sparks were also sometimes seen on the surfaces of the cylindrical porcelain parts of Types 2(*a*), 2(*b*), and 7, and starting from the bottom edges of the caps of all types—except of Types 2(*a*) and 2(*b*), which had their caps embedded in porcelain.

From considerations of voltage-distribution instability, discharges would be expected to occur on those parts of an insulator which naturally have the highest surface resistances; that is, either those parts which remain cleanest or, when the deposit is uniform, those parts where the diameter is smallest. Thus the discharges which occurred on the cylindrical parts of Types 2(*a*), 2(*b*), and 7 were to be expected since these parts had a high resistance because they remained clean; and the discharges starting from the pins of Types 2(*a*) and 4 are accounted for by the small diameter of the porcelain here, since the deposit on these units was practically uniform. The discharges starting from the pins of Types 1, 2(*b*), 3, 5, and 6 are more unexpected since they bridge the parts of the insulator surface which were dirtiest, and would therefore be expected to have a low resistance. The probable explanation is that owing to the very small diameter of the pin the surface resistance in its immediate vicinity was considerable, in spite of the concentration of deposit which occurred there. When the leakage current was large, owing to heavy deposits on other parts of the insulators, the deposit near the pin was dried up and its resistance increased until discharges started across it. On Type 2(*b*) insulators, which collected heavy deposits near the pins but remained fairly clean in other parts, no arcing discharges were observed near the pins. The bad behaviour of insulators having ribs suggests that the deposit which is collected by ribs has serious effects. This is probably because the rings of deposit on the ribs act as collectors for the leakage current, which flows more uniformly over the cleaner parts of the insulator surface. Between such a collecting ring and another ring or the metal pin the current can then flow as a single discharge. Arcs are thus more easily formed, and these, besides having a lower resistance than a number of smaller discharges, also have the tendency to bow out and strike other parts of the insulator, thus short-circuiting comparatively good parts of its surface.

* See Bibliography, (4).

When heavy discharges occurred on an insulator string they were always confined to one or two units, the other units remaining free from discharge. During any one test in bad weather the discharges always occurred on the same units, but the units on which discharges occurred were not the same in all tests. The appearance of discharge on one or two units only, is evidence of voltage-distribution instability between the units of the strings. On some units, which happened initially to be slightly drier than the rest, drying proceeded most rapidly until the voltage across them was enough to cause breakdown. After this the increased current warmed and dried the other units until their resistance was enough to extinguish the discharge. The deposition of dew then began again. Those units which had previously been driest would again be drier than the rest, and it would therefore be across those units that the voltage would build up again and cause discharges.

The tests described in this Part of the paper were necessarily slow, as they depended on weather conditions. They were not brought to a conclusion, but the technique has been developed, the necessary apparatus installed, and a prolonged test is now being undertaken. It is intended that the investigation shall extend over several years. The most important measurements to be made are measurement of the leakage-current surges during fog and, if possible, during dew formation.

The work described in this paper was done in the High-Voltage Laboratory, Queen Mary College. While engaged on the work Dr. Clark held the Ferranti Scholarship of The Institution.

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DISCUSSION BEFORE THE TRANSMISSION SECTION, 15TH FEBRUARY, 1939

Mr. C. W. Marshall: It is of interest to note that insulator leakage losses on 132-kV lines range from 1 to 3 kW per mile, according to weather conditions, so that although not of major importance they are by no means negligible, and if they could be reduced it would be in the national interest. Flashovers, on the other hand, are of primary importance, and the main object in insulator research is still to find means of eliminating them.

I should like to mention that we started with the leakage current at normal voltage as a criterion of the performance of insulators, and Mr. Forrest extended our knowledge of that subject by intensive examination of the wave-form, and also by devising a convenient means of counting the leakage-current surges.

The authors' leakage-current recorder is an ingenious and interesting instrument, but there are much better leakage-current recorders available commercially to-day and it is very regrettable that the colleges should not be in a position to obtain them.

I think it would be useful if the authors would combine Tables 5 and 6 and show the relations between applied voltage, leakage current, creepage distance, and surface resistance coefficient.

The development of the authors' special pin-type insulator with a protective underskirt is interesting, but it seems to me that such an insulator would be deficient in impulse flashover strength, and, further, I think that the modern cylindrical type of corrugation would give still better performance, and would have the additional advantage of being puncture-proof. The question of expense has to be considered, and it is possible that the authors' insulator might have advantages from this point of view.

Fig. A shows three successful types of anti-fog insulators used on the grid. One of them (Type 2), of which at least 50 000 have been installed on the grid, has given excellent results, and it is unfortunate that this particular type was not tested by the authors. I would mention that it is not so satisfactory as the others from the point of view of ease of cleaning. When it is remembered that the standard 10-in. disc referred to by the author as P.1 was accepted all over the world and yet was quite useless in certain of the polluted areas of Great Britain, it must be agreed that the anti-fog units shown here have done a great deal for the supply industry in Britain.

Regarding the general question of insulator testing, it is impossible to determine which is the most rational design of unit by an examination of particular types, and I would strongly advocate the study of the disc and cylinder or truncated cone as a basis for all future work, because any shape can be built up from these fundamental parts.

Mr. N. E. P. Harris: In the present paper I find support for a view that I have expressed in my contributions to previous discussions on similar subjects.* It appears to me that the designs most likely to give good results, when the atmosphere is polluted by salt and industrial fumes, are those which possess the maximum length of

* *Journal I.E.E.*, 1931, vol. 69, p. 830; and 1935, vol. 77, p. 651.

vertical surface washed by rain with the greatest possible length of protected surfaces.

I think we may divide the designs of pin insulators for polluted air into two broad classes. The first includes many variations on pin-insulator design, all bearing some relation to conventional types and able to be justified on economic grounds. The divergence from accepted shapes may be wide because of the variety of conditions which

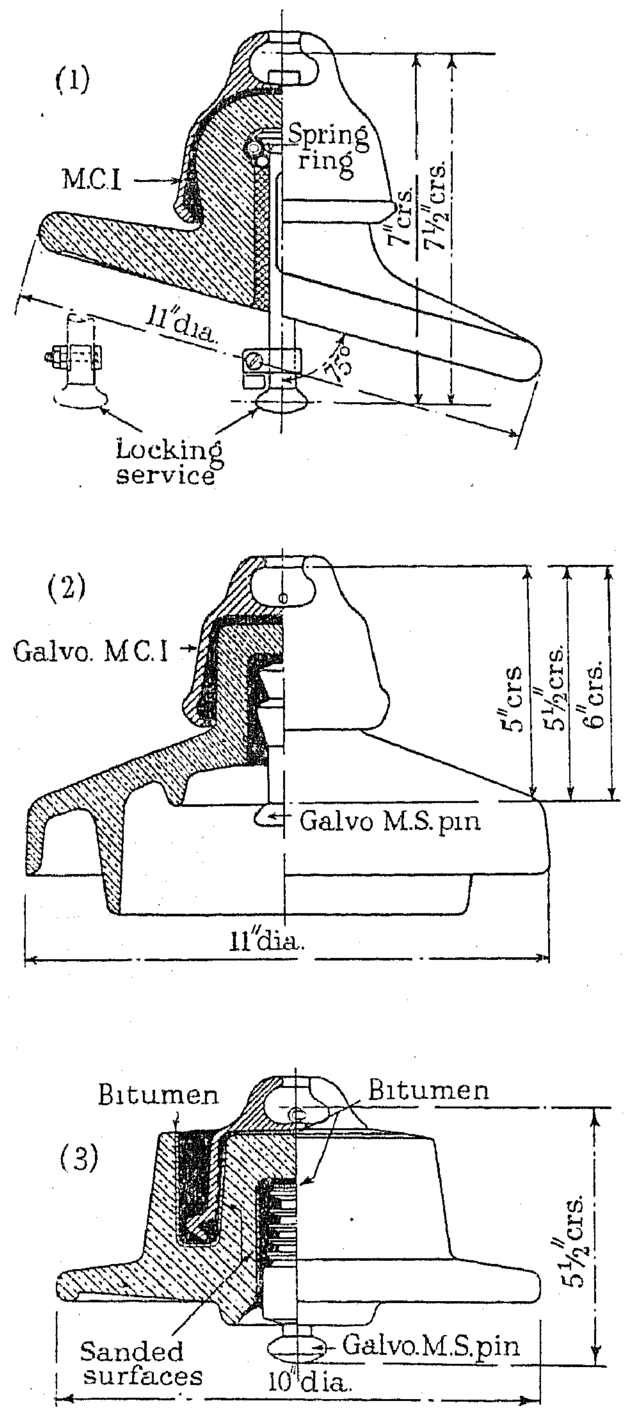


Fig. A.—Anti-fog type insulators.

are encountered. The second category comprises those designs which may be classed as "freaks."

Referring to Fig. 6 of the paper, I place in the first group all except P.1, P.7, and P.8. The design P.1 interests me particularly because I have not previously seen this principle applied to high-voltage insulators, but I should be afraid that in the course of time the upturned portion of the under-shed would provide a receptacle for the retention of dust, sand, or salt, and an excellent domicile for insects.

With reference to the special designs shown in Part 3 of the paper, I am rather suspicious of the prolonged performance of any which depend upon the protective action of a metal cylinder. A pin insulator should withstand normal-frequency flashover with the minimum of damage, so that operation can be resumed immediately the fault is cleared. In the parts of the world where bird trouble is prevalent flashovers on particular poles in the direct line of flight may occur often, and have to be accepted as ordinary hazards. When a metal shield is the means of protection against pollution, I am afraid that flashover would damage the shield and leave the insulator in a worse state than it would have been had the shield been absent.

Is it not fair to say that the efficiency of any insulator is bound to deteriorate under deposit conditions? If we can be sure that a particular design will sustain the working voltage and not give rise to serious leakage-current surges for a period of, say, 12 months under the most adverse conditions, then the times of cleaning can be arranged to suit the operating staff. If I advance this suggestion as a criterion of insulator performance, I am not in disagreement with what Mr. Forrest said in 1936.*

Mr. P. J. Ryle: The authors' standard testing technique in regard to salt deposits affords good control of the several somewhat difficult variables which must be considered. Even if this technique does not ultimately prove to be the right one, it may give results which will afford a basis for the later development of some universally acceptable method of assessing the performance of insulators under salt conditions.

The results obtained with the pin insulators shown in Figs. 7, 10, and 12 are encouraging, but there may be certain disadvantages, one of which has been mentioned by Mr. Harris. Another is that if the metal cylinder is performing its full function, it must be assumed that the upper part of the insulator has more or less failed; and if this is so, and a bird sits on the disc and touches the cylinder, the advantage associated with it will be entirely lost.

I should like to know whether the authors have considered any similar designs for suspension units. I think that there would be grave difficulties there, especially since on a long string the bottom unit may be carrying 30 % or 40 % of the total voltage. It would probably be very difficult to design metal parts giving adequate clearances.

With Mr. Marshall, I am sorry to see that Fig. 14 does not include a certain well-known type of anti-fog unit. This type is shown in Fig. 6 of a paper which I read before The Institution in 1931,† and is now in service in this country in larger numbers than any other anti-fog suspension unit. This insulator, and the type shown in the authors' Fig. 14 as No. 5, are used on more or less parallel lines through similar bad industrial districts on the North-East Coast. So far it has not been possible to say that either is better than the other, but both have proved to be immensely superior to the standard units. Lines where formerly the standard units had to be cleaned every 6 weeks are now left for 12 months without cleaning, yet flashovers are non-existent. Even longer periods between cleaning are contemplated.

I am not quite sure that a testing gantry mounted on

* *Journal I.E.E.*, 1936, vol. 79, p. 401. † *Ibid.*, 1931, vol. 69, p. 805.

the roof of a building gives quite the same effect as regards dirt collection as that met with on towers. The authors found on most of the suspension units that the dirt collected most heavily near the pin, and I found the same thing on a rack which was erected in 1931 on a flat roof near a power station; but in general this does not appear to hold for insulators taken down from a line. On insulators in service on a line, it is generally found that there is a distinct area immediately round the pin where the dirt collection is very slight, although it is extremely heavy outside this area.

I should be interested in this connection to learn whether Mr. Forrest finds a different effect on his test tower at Croydon from that which the authors and I have found on testing gantries on roofs. I agree with the authors that the under-side of the bottom unit of the string is usually cleaner than the others. I am sorry to see that so far the authors' tests on suspension strings have not given any conclusive results, since the general magnitudes of leakage-current surging have been found to be comparatively small. I should like to know whether in their view it would be unfair to maintain an increased voltage or, alternatively, to reduce the number of units per string throughout their long-period trials.

Mr. W. G. Standring: The problem of standardizing laboratory tests on insulators under deposit conditions has often been considered in the past but has not been solved on account of two difficulties—the difficulty of imitating factual conditions in the laboratory and the unstable behaviour of insulator surfaces carrying leakage currents. Salt deposition is more easily imitated than industrial contamination, and the authors have gone a good way towards developing standard salt tests, but the data given in the paper under the heading "Consistency of Test Results" confirm the opinion that, however carefully tests may be specified and controlled, precise results cannot be expected. It seems on this account likely to be impossible to distinguish between insulators of approximately equal merit, but it should be possible to distinguish between a good and a bad insulator, for the tests described show great differences between the best and the worst insulators. For example, the data in Table 6 indicate that some insulators are twice as good as others in respect of the quantities measured.

The leakage current may not perhaps be a strict criterion of the likelihood of flashover, and some impulse flashover tests superimposed on the working voltage would be of value. Apart from impulse tests, the leakage current at working voltage may be as useful a measurement as can be made, for it is obtained under practical conditions, whereas raising the voltage, as for a flashover test, rapidly alters the condition of the surface of the insulator. Leakage-current measurements also indicate the possibility of radio interference, which is undesirable. The frequency of leakage surges is probably significant, as well as their magnitude.

From the data given in the paper it is evident that salt deposition is greatly affected by screening, and from the examples given the transmission engineer should be able to formulate general considerations of design which differentiate good from bad insulators. The good insulators have a considerable extent of surface which cannot be reached by wind from any direction. The screening effect of discs and cylinders is well shown in the paper, and easily understood. The horizontal disc below the pin insulator with the deep bell seems to be a particularly simple and effective arrangement.

In the experimental formation of dew, the lower part of the insulator heated up by the rising steam may be relatively warmer than under practical conditions, so that the effect of screens on dew formation may be exaggerated in the tests.

Mr. J. S. Forrest: The measurement of the performance of insulators under fault conditions is an exceedingly difficult problem, owing to the large number of variables involved and the difficulty of controlling them. For example, the humidity of the atmosphere has an effect on the resistance of the deposit film; the leakage current varies the resistance of the deposit film; and, in addition, there is the very complicated distribution of the deposit over the surface of the insulator. In view of these difficulties the authors' standardization of a saline-deposit test is of importance and interest.

In the Introduction to the paper there is a reference to sources of pollution in general, and I think that it might be well to draw attention to cooling towers as a source of pollution. Large cooling towers are frequently of necessity situated close to switching stations, and under certain atmospheric conditions the precipitation of moisture from the towers may be very heavy. The resulting moisture film has a very low resistance and leads to flashover of the insulators, even if they have been cleaned a few days previously.

With regard to the leakage-current criterion, although this is made fairly clear in the paper, I do not think that it can be emphasized too often that it is necessary to record the magnitude and the frequency of the leakage-current surges over quite a long period. If only a few readings of leakage current are taken the results may be quite misleading. We find that the most convenient way of recording these surges is by means of surge-counters, which are set to record every surge of more than 20 mA. This method has been used at the Central Electricity Board insulator-testing station at Croydon for some years now, and at present twenty-two 132-kV insulator strings, ten 132-kV post insulators, and twelve 220-kV insulator strings are being observed. The total number of surges recorded must be nearly 1 000 000, and I do not think that this amount of recording could be done by any other method.

There is another criterion of performance which is sometimes useful and which depends on the unstable potential distribution that may occur on porcelain surfaces. Consider, for example, the potential distribution on a 5-unit insulator, shown in Fig. B for two values of humidity. Under fine-weather conditions when the humidity is 50 % there is a fairly uniform voltage distribution, as shown by the full line, but when the relative humidity rises to 92 % two or three units carry no voltage while the others are seriously over-stressed, as shown by the broken line. A perfect insulator would give uniform voltage distribution under all conditions, and the degree of departure from uniformity forms a very useful criterion of performance, which may be employed to confirm the results given by other methods. It is interesting to note that the unstable potential distribution which is

characteristic of the porcelain surface is the fundamental cause of all insulator-deposit troubles.

I notice that the diagrams of connections in Figs. 3B and 15 show no device for the protection of the instruments or the operator in the event of flashover; it is worth while to provide such protection.

On page 596 it is stated that only if the relative humidity of the air exceeds about 80 % does the deposit become conducting. We have made a rule that no live insulator testing shall be carried out at a humidity exceeding 70 %, because when the humidity is higher than this the voltage distribution becomes too non-uniform to permit us to differentiate between good and bad insulators.

On page 604 there is a reference to the effect of the application of voltage on the formation of deposit. The Croydon investigations show that if voltage is applied

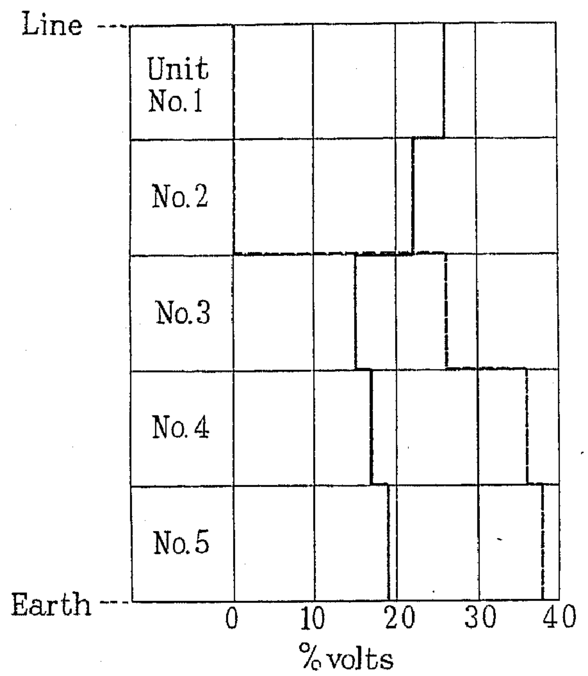


Fig. B.—Voltage distribution on 5-unit insulator.

Relative humidity 50 % ————
Relative humidity 92 % – – – –

the deposit formation is increased. It is necessary, of course, that the voltage should be sufficiently high to cause some discharge; if the voltage is too low to cause discharge it probably will not affect the deposit. This seems to indicate that tests are of little value if the voltage is not continuously, or almost continuously, applied to the insulators for a long period.

With regard to the leakage-current recorder shown in Fig. 16, I suggest that surge-counters might be preferable and would probably be no more expensive.

Regarding the location of insulators under test, we find that the test tower reproduces line conditions very accurately. There is, however, a decided difference between the deposits obtained on the tower and on the rack at ground level; the rack is not nearly such a severe test of insulator performance.

Mr. D. H. Cameron: As the authors point out, the work is being continued under the auspices of the E.R.A. and the chief aim of the present work was the standardizing of the test conditions. The results of their measurements of the performance of insulators show that, with regard to the deposition of salt, when the insulator is not nodded the severity of the deposit depends upon the velocity of the wind. If the insulator is nodded, then the severity is independent of the wind velocity. Nodding is a severe test, and may be misleading. One type of insulator which is well known to give very good results in service was found to be quite satisfactory when the insulator was not nodded, and in fact no surges were recorded by the surge recorder, but when the insulator was nodded the number of surges recorded was over 400, which is quite a bad performance figure. The surge-counter was set to operate at about 10 mA.

With regard to dew formation, this is extremely critical. As Mr. Forrest points out, the voltage distribution of an insulator under deposit conditions is very different from the normal voltage distribution of that insulator, as the region of the pinhole then carries a fair amount of voltage. Under natural conditions the temperature of the insulator will be uniform before dew formation occurs, but after it has occurred, then, owing to leakage-current heating effects and the variation in voltage distribution, the bottom skirt near the pinhole of the insulator will reach a higher temperature than the rest. It is therefore fair to assume that this region will profoundly control the behaviour of the insulator. This assumption is borne out by test results.

If we attempt to establish dew-formation conditions in the laboratory the first requirement is that dew shall form over the whole of the insulator simultaneously; and the second requirement is that if dew formation occurs at an elevated temperature, as described in the paper, care must be taken that the conditions of dew formation do not control the temperature distribution over the insulator. The method described in the paper fulfils neither of these requirements. Owing to convection, steam rises rapidly from the boiler and condenses on the under-surfaces of the insulator first. The bottom shed deflects the steam, and, although condensation occurs on the upper surface of the top shed owing to reflection from the baffle, there is very little condensation on the other upper surfaces. Owing to convection and to direct heat radiation from the steam generator the bottom skirt of the insulator rapidly attains a temperature higher than that of the remainder of the insulator.

The method of dew formation which we are at present investigating is what we call the cubicle method. The insulator is placed inside a large cubicle, the steam generator is placed to one side, and steam fills the cubicle. The temperature-difference over the insulator when this method is employed is only a matter of 3 deg. C., as compared with 15 deg. C. obtained with the previous method.

To sum up, it seems that the method of dew formation adopted by the authors leaves a great deal to be desired, because (1) the dew is not formed simultaneously over the insulator, and (2) direct heating influences the most critical part of the insulator more than any other part.

Bearing these results in mind, certain anomalies in the paper can be explained. For instance, on page 589, under the heading of "Choice of Suitable Severity for Dew Tests," the authors point out that with 4·7 kW input the performance is better than with 3·2 kW. I think that this is due to the direct heating effect, because

with 4·7 kW the extra heating tends to dry up the pinhole and to reduce the severity of the test. Again, on page 603 the authors state that the pin insulator, which has been specifically designed to prevent salt from reaching the under-surface, behaves equally well whether the salt is there or not. This is not due to the fact that the cylinder and disc are effectual in suppressing dew formation, but rather to the fact that the disc deflects the steam and does not permit the saturated air to enter the cylinder as it would do in ordinary testing conditions.

Mr. G. H. Gillam: In connection with the design shown in Fig. 12, I should like to ask whether any tests have been made with this insulator completely shrouded in a metal tube or bell. Apparently the under-side of the bottom shed, i.e. the protected portion, is the only part of the insulator which can be relied upon under certain conditions, and the exposed portion would seem to be superfluous. The authors may be interested to learn that a low-voltage insulator, so completely shrouded by metal that no part of the insulating material is visible, has given excellent results under the difficult conditions imposed by rising steam and dust resulting from the quenching of hot coke in a by-product plant. The principle of covering the insulator with metal has not yet been applied to higher-voltage insulators because of the difficulty of obtaining a reasonable impulse flashover voltage without making the insulator extremely large.

Mr. E. A. Burton: The superior performance of the shielded type of insulator is of interest in view of our experience at the Central Electricity Board's testing station at Croydon. There it has been found that leakage-current surging is generally most severe (on dirty strings, of course) under light rain conditions and when steam or mist is coming down from the power-station cooling towers. In view of this it was felt that some form of shield over the units might be an improvement. The easiest way to apply this was to utilize an oil-filled string (the units having metal shields to keep rain out of the oil) but without the oil filling, and taking care to remove all traces of oil. This arrangement is now in its second winter, and the results are second only to those given by the "oil filled" string, which was found to be entirely free from surging.

Another experiment relating to shielding was not quite so successful. An attempt was made to improve the performance of a standard 132 000-volt transformer bushing, fitted to the recently-installed 250 000-volt testing transformer. It was not convenient to put metal discs or shields over each skirt, and so one large one was fitted at the top. The half of the bushing which was protected kept fairly dry, but the other half became wet and dirty, and flashover occurred from the edge of the metal shield to the half of the bushing which was not protected. Measurements showed that the surface resistance of the half of the bushing which was not protected was as low as 1 megohm, while that of the other half was 5 megohms.

We also have a post insulator on the same equipment (250 kV), made up of seven units of a type similar to P.3. (This type is giving trouble, and we agree with the authors that it is not a good unit.) On measuring the resistance of the units immediately after switching the voltage off, we have obtained values as low as 0·08 megohm per unit.

In designing metal shields for units it should be remembered that a balance must be struck between the air path and the path over the porcelain surface. P.4, for instance, has a very long porcelain surface, next to the pin, in parallel with a very short air path, and under bad conditions we found that the top surfaces are of little value in carrying the voltage. Flashover is likely to start by sparkover from the metalwork across the short air path, and to result in complete flashover of the unit.

Mr. J. A. Broughall: I should like to mention that the requirements for the pin to some extent control the design of insulators for voltages such as 6·6 kV and 11 kV. We have found that, using pins of both wrought iron and mild steel (galvanized) and insulators of various shapes, we have had to replace the pins in periods up to 25 years when the insulators were still perfectly good. We are forced to the conclusion that it is necessary to arrange for frequent painting of the pins in order to give them a life equal to that of the insulator. It is thus necessary to paint the pins in order to preserve them, and this consideration settles the shape and minimum diameter of the inner shed, because it is necessary to be able to paint up inside it. Although the authors' tests are short-duration tests, they have an important possibility of extension in the direction of relating pin corrosion to the deposit problems which have been investigated.

I should be glad if the wet flashover voltage of the insulator could be given in Table 5 as well as the dry flashover.

Some of the pin insulators shown in Fig. 6 will obviously be many times as costly as the others, and if the authors are not able to give actual costs perhaps they could give relative cost factors.

Prof. J. T. MacGregor-Morris: I should like to say a word or two on possible reasons why the results of laboratory tests may differ from those of tests which are made in the open. A number of years ago I had to measure the wind velocity at various places along the East Coast, on cliffs and on lighthouses, by means of an electrical anemometer. I used to note the reports which the lighthouse keepers gave of whether the wind was steady or gusty, and then observe how great the fluctuations of the wind actually were from rapid measurements by means of the electrical anemometer when a so-called "steady" wind prevailed. The first point which became perfectly clear was this, that when a wind is called "steady" by a lighthouse keeper it ranges at least from 5 to 15 m.p.h., so that a gusty wind must have an enormously wide range.

My next point is with regard to the position of testing gantries. If a "steady" wind is blowing I suggest that the wind at the top of the gantry will by no means be steady either in direction or in magnitude. I have studied the wind distribution around the edge of the cliff at Cromer, using an anemometer supported at various heights up to 13 ft. It is quite common for a general "on shore" wind to be blowing in an "off shore" direction on the surface near the edge of the cliff. This can easily be demonstrated when walking along an esplanade if the wind is blowing "on shore"; for if one tries to throw a piece of paper over the edge, though it will be carried quickly to the very edge it is then caught and whipped back by the wind, showing the presence of a large eddy. It is eddies such as these which I consider

require careful consideration when a suitable site is being chosen for a testing gantry.

Mr. J. P. Jeffcock: Insulators under deposit conditions have the unfortunate habit of causing radio interference, and as I am associated with the choice of sites for a series of radio receiving stations, this phenomenon is of great interest to me. At these stations signals are received having less than 1/1000 of the strength of normal broadcast signals, so that the fact that the broadcast listeners near a transmission line are getting satisfactory reception does not necessarily indicate that a highly sensitive receiving station would be free from interference near the same line. Clearly, sensitive stations should not be placed near such lines, but there are many factors, both technical and administrative, which govern the choice of sites, and sometimes proximity to lines ranging from 6 kV to 132 kV is unavoidable.

Another difficulty is the scarcity of information available at present concerning interference caused by transmission lines. The last paper dealing with this subject, so far as I can recall, was that by Messrs. Gill and Whitehead,* but since it was published further data have been obtained and are unfortunately somewhat contradictory.

The laboratory method of insulator testing which the authors have devised can hardly be a complete solution from an interference standpoint, because the severity of interference is partly governed by the electrical constants of the line, and in a laboratory where space is restricted it would seem to be impossible to reproduce those factors. However, the severity of interference is presumably proportional to the magnitude of the leakage surges, which I understand is also the criterion from the point of view of the transmission engineer. If, therefore, an insulator can be designed which will reduce the magnitude of those surges, it should automatically reduce the severity of interference produced under given line conditions.

I should like to ask the authors whether they can give any further information about their plans for future work on the radio-interference aspect of insulator testing. Also, it is to be hoped that they will work in close collaboration with the General Post Office and the Central Electricity Board, who have considerable previous experience in this sphere, not all of which has been published.

Mr. R. C. Andersen: I agree with Mr. Jeffcock that the question of radio interference has not received the attention it deserves. For a long time past I have been of the opinion that the problem of deposit on insulators is a high-frequency problem, and should be tackled as such.

Most of the pin-insulator and suspension-insulator designs which are in use to-day are of relatively high capacitance, whereas to combat the deleterious effects of radio interference, low-capacitance insulators—in my opinion—are necessary. The high capacitance associated with deposits would seem to accentuate radio interference.

To minimize if not to eliminate this interference, a heavy reduction of charging current by means of a similar reduction in insulator capacitance should be the object. In addition, it would seem necessary (*a*) To provide insulator surfaces which can be cleaned, and cleaned rapidly. (*b*) To provide a form of flux control within the insulator, in order to retard the formation of surface streamers.

I visualize that an insulator having the features described would be tubular in construction, with a generous metal rainshed on top. The tube (not necessarily air-filled) would be relatively long.

Mr. E. J. C. Dixon: I should like to suggest that more attention might be given to the problem of designing insulators for high-frequency transmission lines. In wireless work it is desirable to omit sheds altogether, owing to the capacitance loss which they introduce at high frequencies. Thus designs often take the form of developments of simple cylinders, and for this reason I agree with the suggestions made by previous speakers that simple geometrical shapes should be investigated. The use of low-loss materials is helpful in high-frequency work, and owing to the superior mechanical strength of such materials insulator sizes and capacitances can be reduced by their use. Since low-frequency transmission lines are often subject to stresses at high frequencies, I am prompted to ask whether an attack on the high-frequency aspect of the problem would not also be advantageous to engineers concerned with low frequencies.

Mr. J. H. C. Brooking: The discussion has principally been devoted to insulator design, and the authors' novel idea of shielding the insulators has hardly been touched upon, but it might be given more attention than it has received. I do not think the metal cylinder will prove satisfactory when exposed to the atmosphere unless it is protected in some way. Is it worth while to consider using instead a cylinder made of some insulating material which will stand exposure to the air, for protecting, perhaps, a much greater portion of the insulator?

The question of air-raid precautions against troubles on overhead lines is attaining increasingly greater importance, and the paper may give us a lead for the future.

[The authors' reply to this discussion will be found on page 621.]

MERSEY AND NORTH WALES (LIVERPOOL) CENTRE, AT CHESTER, 21ST FEBRUARY, 1939†

Mr. W. Fennell: The apparatus devised by the authors reproduced the conditions of a brine storm very closely, as may be judged from the description which follows of the conditions experienced in the Weaver valley about 14 years ago. First, there was a gale of something like 40 to 50 m.p.h. Secondly, there was a very high tide due to the direction of the wind being such as to force the water into the Mersey estuary. Salt-water spray from that estuary was brought along the Weaver valley, certainly as far as Knutsford, and some of it reached the very centre of England, via the Severn estuary. This gale persisted throughout the morning, and brine crystals similar to those shown in one of the authors' slides appeared on the insulators. At about 2 p.m. the gale ceased, and a condition of high humidity replaced it. (I do not think the authors need be concerned about the

* *Journal I.E.E.*, 1938, vol. 83, p. 345.
† Joint meeting with the Chester Engineering Society.

exact way in which the dew is formed, because a humid atmosphere, however produced, causes the crystals to dissolve and cover the insulator with a conducting layer of brine.) The insulators were unusable until about 40 hours later, when it rained, and within 10 minutes of the commencement of the shower we were able to use the lines. The rain was not heavy, so it obviously washed the upper surface only of the insulators. We never learned what became of the salt on the under-surfaces, but we presume it dried later, and scaled off. Several of our linesmen tried to clean the insulators along a short but important section, but the attempt was a failure.

I feel some doubt as to the methods adopted by the authors for estimating the merits of insulators, because I think that the only proper criterion for the judging of an insulator is the voltage which causes a flashover. The user does not mind about leakage currents of a few amperes occurring under extraordinary conditions; what he is concerned with is that there shall be no flashing-over. I am therefore afraid that the authors' laboratory apparatus designed to indicate leakage—although of great interest to the students—will not lead to the discovery of the best shape of insulator to stand the worst conditions. A similar criticism applies to the authors' oscillograms.

I should like to know whether in the authors' opinion brine conditions are the worst that can occur. If they agree that this is so, then from tests under those conditions combined with tests under some moderate deposit conditions, such as obtain in a city or near a railway or an ordinary works, it should be possible to design an insulator having the required factor of safety for use throughout this country.

As regards pin-type insulators, the result of the test on Types P.2 and P.8 indicates that what we require is within reach, and I suggest that a design between Types P.6 and P.4, provided it would give a safety factor of 2 under brine conditions, could be adopted as a standard. Once such an insulator is produced, I suggest that all the other types should be abandoned. Mass production of the standard type will then give us satisfactory insulators at lower prices than we are paying now.

Designs like P.7 and P.8 are far too expensive for ordinary use, and, I suggest, too fragile. I do not think they will be used in the future even for specially bad positions, because suspension or post insulators will be used for such conditions at 33 kV and upwards.

I have a point to raise with regard to the question of turbulence. Referring to Table 6, Tests (*a*) and (*b*) were carried out in a horizontal wind, but I am not sure that the wind was horizontal at the insulator, where the cross-arm supporting the insulator is in the air stream. With the wind at right angles to the face of the cross-arm, the latter forms an obstruction and produces local turbulence, liable to deposit salt on the under-sides of the sheds. I therefore suggest that it would have been much better if the tests on Type P.9 had been made (1) with the skirt alone; (2) with the plate alone, and then with the skirt and plate combined.

I cannot see how one can measure the "surface-resistance coefficient," as defined at the foot of Table 5, in a reasonable time. Such a measurement is very much more involved than measurement of the creepage distance, i.e. the contour length, by using a piece of string. I suggest that as neither method is anything more than a rough guide, the "surface coefficient" method will not survive.

I should like to know something more about the Type P.1 insulator, the illustration of which in Fig. 6 is not clear.

Turning to Part II of the paper, I think it is very unfortunate that the authors have departed from the accepted principles of investigation by not making a test with the plate by itself. Such a test might produce a very good result and show the skirt to be unnecessary. It introduces a new and dangerous form of nesting place for birds.

It is also unfortunate that the authors designed a new insulator to test the skirt. If a skirt had been added to some of the insulator Types P.1 to P.8, which they had already tested, a very useful range of comparisons would have been available. A similar remark applies to tests with plates only. One disadvantage of a metallic skirt is that it involves a longer pin, which greatly increases the cost, for a given stress.

It would be interesting to know why the authors did not apply their brine tests to some of the disc insulators mentioned in Part III. One important reason why I suggest brine tests for these disc insulators is that records exist of their behaviour under bad service conditions, and therefore the value of the "brine machine" could be estimated by comparison of the experimental results with the known performance in practice.

Mr. A. N. Mansfield: It may be interesting to compare our actual experiences in North Wales with the authors' test results. When we started transmitting at 33 kV we adopted an insulator very similar to Type P.3, and this insulator very soon proved unsuitable. Repeated flashovers took place, and the line voltage had to be reduced to 20 kV until the insulators could be replaced. Finally, after trying several types, we arrived at an insulator intermediate between Types P.5 and P.6, and this has proved entirely satisfactory and completely free from flashovers due to salt. The lines concerned are in our coastal area, where conditions are bad.

The first insulator had a surface exposed in a horizontal direction representing about 55 % of the total leakage path, and on the second type this figure was down to 33 %.

For salt conditions a certain proportion of shielded surface appears essential to safe working.

A further point of interest is that the Type P.3 insulator has never given any trouble when working at 20 kV. At one time we had this type on a double-circuit line, one circuit operating at 33 kV and the other at 20 kV; the former was always flashing-over, and the latter was quite stable. This disproves the theory that in practice salt deposits are cumulative, and will in time cause any size of insulator to fail at a given voltage.

An outstanding feature of our experience is that, except for one case, we have no reported instances of flashovers due to salt at voltages under 33 kV. The one exceptional case was that of an 11-kV line which runs down to the sea shore.

I agree with Mr. Fennell that the real criterion of per

formance from the operating engineer's point of view is the flashover voltage, but leakage-current measurement is a very useful laboratory test and is perhaps necessary where a searching investigation is being carried out. I suggest that the two measurements should be correlated in some way.

It is pleasing to learn that extended investigation of this subject is to be made under the direction of the Electrical Research Association. I hope that some of their findings will be incorporated in the British Standard Specification for transmission-line insulators, which at present affords no guide in respect of insulators for use in exceptional conditions.

With regard to the suggested insulator design shown in Fig. 12, I consider that this would be subject to bird troubles in its present form.

Mr. G. F. Davies: Mr. Fennell mentioned that he does not regard dew as an important factor, but my experience tends to make me think otherwise. About 2 years ago there was a severe westerly gale during the day, with no rain, and conditions at night were favourable for dew formation. One of our important lines, which runs near the coast, would not hold in at all. An hour or so after daybreak it could be made alive, but more troubles occurred during the night. We had to be content with washing and changing the insulators during the night and making the line alive during the daytime. This condition persisted for 4–5 days.

I note that the magnitude of the leakage-current surges is the best criterion for judging an insulator during laboratory tests. Does this mean that the frequency and amplitude of these surges are the best means of differentiating between insulators from the standpoint of insulating values?

What would be the effect on the leakage current if wooden cross-arms were used and the pins not earthed?

Table 5 suggests that the best insulators are those which have the highest surface-resistance coefficient. Is any research being carried out to find the minimum safe figure for a definite voltage?

In Table 5, Types P.3 and P.5 rank 4th and 7th respectively in order of merit, and the shed diameters and flashover distances are about the same for both, yet the creepage distance of P.5 is almost double that of P.3. Why is this?

Very little is said in the paper about voltage distribution, yet I believe this is extremely important so far as the prevention of flashovers is concerned. I understand that the best insulator is that in which the surfaces subjected to the most fouling (i.e. the sheds, in pin-type insulators) lie along equipotential lines in the electric field.

A few days ago I inspected some insulators which had had 30 years' continuous use on a 10-kV line in a mountainous district. The insulators were of an old German type, made of white porcelain. They were very similar to the modern telephone insulators but had two very deep, well-protected skirts, extended down to the level of the outside porcelain. The pins were cemented in. There was hardly any trace of dirt or deposit on the interior surfaces of the insulators. The edge of the skirt nearest the pin had been roughened and all the glaze eaten off, otherwise the insulators were in excellent condition. These insulators were fixed in oaken cross-arms, and the pins were not earthed.

The tests on Type P.9 show a great improvement over the test results for Type P.3 given in Table 6. But why have a metal cylinder; why not a bakelite one, or even a porcelain one? Metal becomes corroded; also, does it not upset the voltage distribution? Probably trouble would be caused by birds—particularly sparrows and tomtits—nesting in such ideal surroundings. Large discs might cause trouble on road-crossing duplication, or on steep slopes, by upsetting clearances.

With suspension insulators, presumably owing to better voltage distribution, there is less risk of flashover.

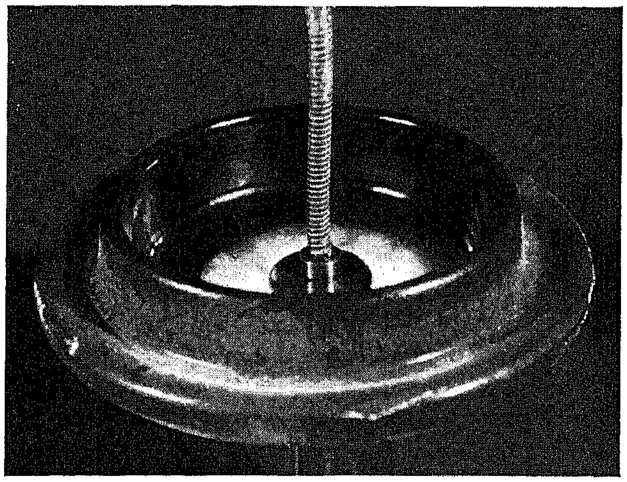
We have a large number of Type P.7 motor insulators on our system, on lines operating at 33 kV, as well as at 11 kV, and in no case have we had deposit trouble. For other reasons, these insulators have caused trouble during lightning storms. No trouble has been experienced due to failure of the porcelain under tension.

There is a fault which is rarely mentioned, yet might possibly come under the heading of deposits, and that is sleet trouble. I can understand why sleet troubles occur on our system with westerly or northerly gales, but not with easterly ones. Salt would be in solution in the westerly or northerly winds, and so we might expect trouble. Pure snow is a good insulator, and heavy rain does not cause a flashover (supposing the insulators to be clean), yet sleet under certain conditions will cause a line switch to trip again and again. I have known lines insulated with 33-kV type insulators, but operating at 11 kV, to fail to keep alive under sleet conditions. Generally, though, very little damage is done to the insulators by these flashovers.

Mr. W. Holttum: The object of this research is presumably to discover the ideal form of insulator, or the nearest practical approach to the ideal, for use under deposit conditions. It seems likely that this would also be the ideal form for any conditions, and that bad conditions should be provided for by using a larger insulator. The general principle would appear to be that the top and sides should be of a form to be easily washed by the weather, and that the under-side of the shed or sheds should be corrugated in order to give the longest possible leakage distance.

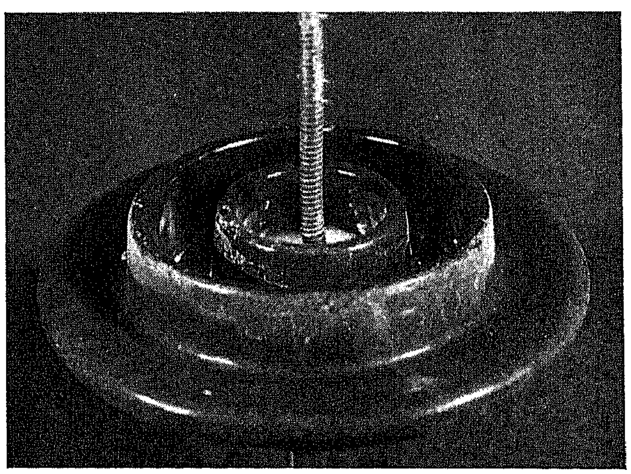
It should be recognized that the authors are trying to solve a problem to which there is probably no precise solution, and on this account they are deserving of our sympathy, but it also follows that they should constantly bear in mind that the value of their work must depend upon sound foresight and careful planning in order to obtain results of the greatest possible use. It is therefore satisfactory to note that this paper is to be followed by further work which is being done by the Electrical Research Association, and it is to be hoped that these discussions will carry their full weight in guiding this work.

There should be a clear understanding as to what the user of the insulator is going to do with regard to cleaning. It is probably intended that no cleaning shall be done under any conditions, though in extreme cases it may be unavoidable. The skirt arrangement resulting in an enclosed space underneath seems, therefore, objectionable, as even though a harmful deposit took years to form,



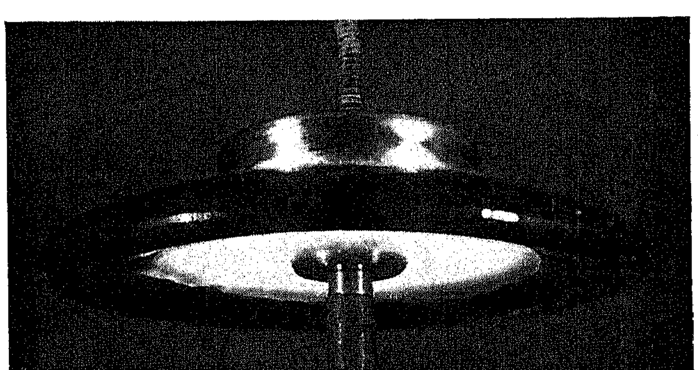
(i) Salt sprayed horizontally: surface discharges (shown) at 35 kV, sparkover 40 kV, humidity 85 %.

Clean: sparkover 75·8 kV, humidity 60 %.



(ii) Salt sprayed horizontally: surface discharges (shown) at 40 kV, sparkover 47 kV, humidity 85 %.

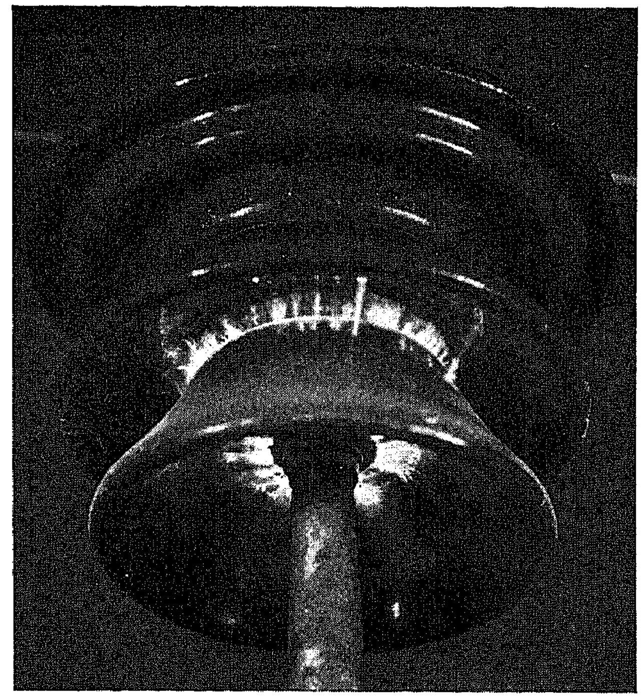
Clean: sparkover 74·8 kV, humidity 60 %.



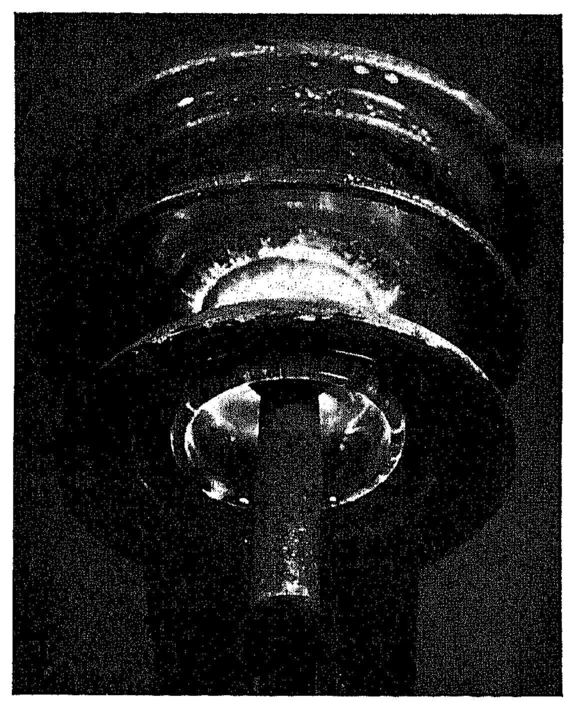
(iii) Salt sprayed horizontally, both sides were conducting.

Clean: surface discharge (shown) at 50 kV, sparkover 59 kV, humidity 60 %.

Fig. C



(i) Ordinary type. Surface discharges at 40 kV, humidity 80 %.



(ii) Sea-fog type. Surface discharges at 50 kV, humidity 80 %.

Fig. D.—33-kV insulators, salt-sprayed. In both (i) and (ii) all surfaces were covered with salt, except underneath the pin shell.

cleaning would be virtually impossible. Moreover, under most deposit conditions there is a corrosive atmosphere which might give a short life to the metal parts unless these were made very heavy.

The test results on the eight insulators shown in Fig. 6 are disappointingly consistent with the surface leakage distances, P.1 being the outstanding exception. I should like to know why this type has been included, as it seems to come in an entirely different category from the rest, having a metal hood and a channel beneath the shed which would hold moisture. Generally, therefore, the leakage-surge results give no guidance in regard to what is the best shape.

Will the authors please state the relationship of the voltage wave to the oscillograms in Figs. 5 and 11?

The method of comparison by measuring leakage-current surges has the advantage of being more convenient than by flashover testing, and probably gives more consistent results, but as the flashover test is the criterion of real interest the relationship between the two requires investigation.

I am inclined to the view that the best form of insulator can be best settled by application of the common-sense principles referred to early in these remarks, and that the chief function of testing is in order to provide data from which to settle the relationship between size and working voltage.

[The authors' reply to this discussion will be found on page 621.]

NORTH-WESTERN CENTRE, AT MANCHESTER, 28TH FEBRUARY, 1939

Mr. J. L. Langton: My first personal contact with power-line trouble due to smoke pollution occurred in 1920 in connection with a 6-kV line between Stoke and Milton, on which in winter the circuit-breakers would frequently operate. The dead line was sectioned and tested by means of a low-voltage d.c. ohmmeter, and the trouble was located at a trifurcating box where the line passed into an underground cable. The insulators were completely covered by a cowl and were black with deposit. As soon as these insulators were cleaned the insulation resistance of the line (section) considerably increased and the trouble was removed. The trifurcating box should be of a type in which the insulators are exposed to the cleaning action of wind and rain. In Fig. 6 the insulator P.1 is shown as being protected with a metal cover and having a plate underneath. From the leakage-test result (Table 6) the insulator appears to be good, but in view of the above experience I would not recommend it for localities where deposit conditions occur. It is desirable also to avoid a plate at the bottom of an insulator, on account of accumulations of snow (plus salt) which might easily cover the insulator, and, of course, because the plate serves as a bird-rest unless *chevaux de frise* are provided.

In 1923, at the Manchester College of Technology, we commenced to observe the formation of deposits due to smoke. Various Post Office insulators and parts of glass line insulators (Hemingray type) were tried, and the observations were continued for several years. The conclusion arrived at was that on the top of a building like a college the adverse conditions encountered in line practice did not occur. The fact that disappointing leakage-current results were obtained by the authors on suspension insulators (page 606) suggests that Queen Mary College is not representative of a bad site. Moreover, the worst leakage (page 607) was only 10 milliamp. whereas Forrest* observed current surges up to 100 milliamp. The bad-weather leakage-current results of Table 8 are not very conclusive, and I doubt whether leakage current in a laboratory test should be accepted as a criterion for comparing insulators.

In 1927, gales round Britain caused failures of coastal lines due to saline deposit. On a 33-kV line serving the Lothian area, a heavy salt-laden fog from the sea extended for some considerable distance inland on the 21st November. The saline deposit caused flashover of a large number of insulators of the ordinary type, and interrupted the supply. Similar trouble occurred on the Mid-Cheshire lines: Mr. Fennell reported that two gales brought salt spray over and put the lines out of action—in one gale for nearly 30 hours.

The matter of a new design of insulator was referred to me, and at the College of Technology we investigated the problem with salt atomizers. The spray could be projected horizontally and at an angle of 45° below the horizontal, i.e. the spray was "nodded." Various kinds of insulators were tried, usually types with a smooth shell underneath, and even dishes under the insulator were employed to baffle the spray and prevent it from coming underneath; but these baffles were discarded for the reasons already given above. Discs with and without under-sheds were tried in a chamber the humidity of which could be accurately controlled up to 100 %, but for photographic confirmation of difference in behaviour as regards surface discharges the humidity was lowered to 80%–85%. The criteria for comparison were (*a*) character and amount of surface discharge at lower than sparkover voltage, and (*b*) sparkover voltage. The limits for repeated conditions were closer than those given on page 606.

Fig. C (see Plate 3, facing page 616) shows the advantages of under-shedding, which lie in the lowering of the potential gradients on the surface.

These investigations led to the design No. H.11834, referred to in Fig. 6 as P.5. Insulators of this design were put into service on the Lothian coastal line, and there has been no trouble there since. A comparison of this type and the ordinary type (P. 5656) for the same line voltage is given in Fig. D (see Plate 3). The salt deposit was sprayed on both insulators, but the inside of each pin shell was cleaned. For P.5656, above 40 kV the surface sparking from the pin extended so rapidly that sparkover occurred below 50 kV.

The authors arrive at the same result—that P.5 is better than P.2, P.3, and P4 (and I would include P.1). Insulators P.6, P.7, and P.8 are larger or longer, and in the case of P.7 there is more under-shedding. Consequently, they show up better and, for saline deposit caused by spray near the coast or by salt in a dry state carried

* *Journal I.E.E.*, 1936, vol. 79, p. 401.

inland, prove that the under-shedding principle is right.

Now let us see whether the principle is not also right for the suspension type of insulators. The authors state (page 599) that, of the insulators shown in Fig. 6, P.7 behaved best. It is $13\frac{1}{2}$ in. long, and is really a post type with five cemented joints. If the insulator were of double or treble the length its behaviour as regards leakage current (or "voltage," as in Table 6) would clearly be better still. By modifying the metal joints a suspension insulator is thus obtained with under-shedding.

The authors suggest a standard saline-deposit test for pin insulators but not for suspension insulators. Had they carried out their test on even two suspension units in series the insulators of Fig. 14, with the exception of Nos. 7, 12, and 10, would have behaved badly. Leaving out of account a type like No. 7, in which the porcelain is in tension, then a deeply under-shedded type like that of Fig. 6 in P. J. Ryle's paper* should have a good performance.

Regarding insulator P.9 (Fig. 10), the objections to this design can be summarized as: (i) accumulation of snow and salt; (ii) effects of metal shed on arc-over, corrosion, erection; (iii) height; (iv) short distance to pin (for spray in gale); (v) under-surface coated with salt in sea-fog, no deep under-shedding, no chance of washing off by wind and rain; (vi) invitation to bird-nesting.

I hope that some day the authors will be able to produce a laboratory test which will indicate what would be the performance of the insulator under adverse line conditions. The reason why I think their saline test inadequate is that, whereas ordinary insulators can flash-over at line voltage under dew or fog conditions when voltage surges are present, the authors have not succeeded in obtaining a flashover at line voltage (see Table 6).

Finally, I should like to see tests conducted at the sea-coast similar to those carried out by Mr. Forrest for the C.E.B. at Croydon.

Mr. F. R. Perry: Mr. Langton has mentioned my name in connection with some work I did under his direction a number of years ago when I was a student at the Manchester College of Technology. My most vivid recollection of this particular research is climbing a telegraph pole, on most Saturday afternoons during a year, in order to observe the rate of accumulation of dirt deposits on insulators mounted on the pole. The telegraph pole was situated only a few yards from railway lines (at Collyhurst Junction) where coal-burning engines were passing to and fro many times an hour. The amount of deposit accumulated in 3 months was quite large, much larger than was obtained in 18 months on insulators placed on the roof of the College of Technology. The College is situated in a comparatively bad area, as there is a large railway station about $\frac{1}{2}$ mile away and an elevated railway track about 200 yd. away. It was clear from these two tests that insulators placed on high buildings were very largely sheltered from the worst effects of dirty atmospheres, and in service much more severe conditions could obtain on a transmission line. To accumulate deposits on insulators under free atmospheric conditions is a lengthy process, and even if the process is accelerated by means of a controlled atmosphere the same difficulty obtains in the two cases, i.e. of devising a reliable method of gauging the electrical performance of insulators under these adverse conditions.

As regards the technique devised by the authors for covering the insulators with salt deposit, what is the effect of the pole structure, in the field, in controlling the manner in which deposits are distributed over the insulator surface? Probably the pole always has a beneficial effect in shielding the insulator, and the "nodding" technique described in the paper gives a much more severe condition than would be met in practice.

I am not clear as to what the authors mean by the term "leakage-current surge." Oscillogram No. 3 of Fig. 5 shows two current/voltage loops in which the currents were 0·5 and 0·9 milliamp. respectively. Apparently the current changed to the higher value quite quickly and for only a short time. Is this a "leakage-current surge" under the authors' definition, or are they referring to the short-time phenomenon as shown at one end of the Lissajous figure in No. 4 oscillogram? This latter is clearly a short-time current pulse which is superimposed on the main leakage current and which may vary widely in magnitude every few cycles. This would appear to be the important value to measure when determining whether the insulator surface is approaching a condition where flashover might occur. I doubt whether the milliammeter which was apparently used in general for leakage-current measurement would indicate the magnitude of these pulses correctly if they varied every few cycles. The cathode-ray oscillograph would record these individual pulses, but some form of moving recording film would be necessary to separate the individual peaks.

The results given in Table 2 are rather inconclusive as the leakage-current surges vary in value by a factor of 10 to 1 in two tests of supposedly identical conditions. I conclude that the authors have selected the dew severity test from purely arbitrary considerations without much reference to the results given in this Table. It is clear, however, that before such a test could be adopted for inclusion in a standard testing specification it would be necessary to define the conditions for producing dew rather more exactly than the authors have done.

They quote, as one criterion of insulator performance, the voltage at which the leakage current exceeds 50 milliamp. I gather that the testing transformer used was of limited capacity and hence it was not possible to obtain a flashover-voltage value on an insulator covered with salt deposit under the dew test. If this figure could be obtained, would it not be of more interest than the voltage values given in the paper?

A number of different insulator designs are shown in Fig. 6. Selecting three of these, namely P.6, P.7, and P.8, there is a big difference in the shapes and appearances of these insulators, yet they all behave in a fairly satisfactory manner under the salt-and-dew test. It is not clear what is their common characteristic which causes them to behave well under these conditions, and it would be of interest to know whether the authors can predict from the appearance of an insulator whether it is likely to behave in the manner desired.

In examining new insulators which have been designed to meet one specific condition of operation it seems to me

* *Journal I.E.E.*, 1931, vol. 69, p. 805.

essential to consider how these insulators will behave under other abnormal conditions which may be met in service. For example, P.7 and P.8 appear to be of a type which would cascade under a wet-flashover voltage test, and I believe they would certainly cascade under impulse voltages. The sheds of P.8 seem to be rather thin, and it appears that punctures might occur through the sheds if the insulators were struck by lightning.

Insulator P.9, with its metal cylinder, is a very ingenious device to ensure that at least one portion of the insulator surface is free from deposited salt. The satisfactory operation of the insulator in service appears to depend, however, on whether the sparking voltage between the cylinder and the pin will be maintained at a sufficiently high figure under salt-deposit conditions. The authors themselves suggest that the whole of the upper surface of the insulator from the conductor to the protective cylinder may be short-circuited by conducting surface deposits, so that the full line-to-earth voltage across the insulator would be developed between the cylinder and pin. With the voltage applied between the cylinder and pin when the insulator is clean, the flashover voltage is given as 60 kV. If the surfaces of the pin and the cylinder became dirty and hence roughened by the accumulation of deposit, it would appear that a much smaller breakdown value would be expected between the cylinder and the pin. In fact, it might be expected that a breakdown voltage of only 10 kV per in. would be obtained under adverse conditions, and as the distance between cylinder and pin is $1\frac{3}{4}$ in. the breakdown voltage of the gap would be less than the working voltage on the line.

The authors have decided to study the formation of industrial-type deposits (i.e. dirt as opposed to salt) on insulators without voltage being continuously applied. While I do not necessarily agree that this is as satisfactory as keeping the voltage applied during the whole time the deposit is being formed, it appears to me that when measuring leakage currents across the dirty insulators it is essential to apply the voltage for a reasonable time beforehand to ensure that steady-state conditions are reached before any measurements are taken. The records given in Fig. 17 show a big difference in the magnitude and duration of the leakage currents between the first and second minutes of voltage application. It would be interesting to know what records were obtained after 5 min. or 30 min. of voltage application, as presumably the leakage currents might be still further reduced in magnitude and duration. This latter condition would more nearly correspond to service conditions, where most lines are alive during all weather conditions. If a line, having been dead, is switched into service during fog or mist, I imagine it may be necessary to dry out the line by the gradual application of voltage. This, however, is a special case. Perhaps the authors could state whether the conditions shown during the second minute of Fig. 17 are substantially the same as would obtain after half an hour.

Mr. H. G. Bell: There has been some discussion as to the relative value of laboratory tests and tests on insulators and lines. There is great difficulty, particularly in a question of this sort, in reconciling laboratory results and results obtained in practice. The laboratory results must be obtained first, because before an insulator can be used on a line it must be produced in comparatively large numbers; if, for example, we take 6 towers to the mile and 11 insulators per string, practically 200 insulators are required per mile of 3-phase line. The results of the laboratory tests must be confirmed by experience in the field, and there is difficulty in reconciling the statistics obtained with different types of insulator owing to the wide variation which occurs in atmospheric conditions along the line.

A most important point in the design of an insulator is the ease with which it is can be cleaned, and in this respect the insulator suggested by the authors is not very satisfactory. There may be something yet to be learned as to the best way to clean an insulator: some people use water, others dry rags, whilst still others use various kinds of metal polish.

Another feature of increasing importance is radio interference, and in the near future the choice of insulators may be materially affected by their behaviour in this respect.

Mr. S. Farrer: Some time ago we were trying, at the Manchester College of Technology, to produce deposits in the laboratory similar to those obtaining in service, particularly those due to a polluted industrial atmosphere. One attempt was made by taking an insulator such as might be used for 22 kV or 33 kV, and making it alive in a chamber in which fumes and smoke were produced by burning oil on rag or cotton waste. There was obtained a kind of fluffy deposit, formed from a loosely-knit succession of soft sooty particles, which was not at all like the kind one finds in service, which is hard, adherent, and even durable. Possibly this consists of what remains after the wind and rain have cleared away all the loose dirt, leaving the layer of deposit built up from successive layers of a sticky component obtained from smoke, etc., which seems to harden with time. If the voltage on the insulator is sufficiently high the effect is to cause excess of the deposit near the edges of the corrugations and sheds, whilst along certain surfaces where appreciable voltage-gradient occurs there may be only a negligible amount.

If the voltage on the insulator is such that corona occurs near the metal fittings the tendency is for both conducting and insulating particles to be kept away, and for the thickest deposit to form at some distance from these metal fittings. The action is very similar to that which obtains in electric precipitation.

The author's criteria for judging insulators (Table 6) are interesting, but I submit that it is also essential to know the factor of safety against flashover both by power frequency and by impulse, and thus the capability of insulators of different shapes to retain satisfactory characteristics in spite of the deposits which form upon them.

It is not quite clear why the authors changed their basis of comparison for the pin insulators in Table 6 for a different criterion such as was adopted for the suspension types of Fig. 14.

It is interesting to note that the deeply corrugated P.7 insulator (Fig. 6) is the best of its group; whereas, turning to Fig. 14, we find with the surge discharge method of test that No. 4, without under corrugation,

is amongst the best of its group. In the first case the pollution comes from salt solutions and in the second from industrial deposits. The deposit conditions may therefore be divided into two main types, requiring two different insulators, one particularly useful for the industrial type of deposit and the other for operation in seaside districts.

It must not be overlooked, however, that we have many industrial areas near the sea-coast where both types of deposit may form simultaneously, and eventually attempts will have to be made to find an all-purpose type of insulator. If No. 4 insulator (Fig. 14) were subjected to sea-salt conditions, i.e. the salt foam or spume carried upwards and blown by the wind, a completely continuous saline solution could form on the under-surfaces; and then with moisture or other deposits on the top surfaces, which are almost horizontal, it seems that these insulators would become completely short-circuited. Thus, whilst this type may be good for industrial conditions, and I believe they have been found so in Central Germany, I submit that they would have a very poor performance when used near the seaside. I believe, however, that some of the Fig. 6 insulators would withstand some industrial-deposit conditions at least fairly well, and that insulators on the lines of P.7, for example, should therefore have a more general application.

A statement has been made to the effect that a large amount of deposit forms on corrugations. To my mind this does not necessarily matter very much, provided that such deposits form on surfaces over which there would normally be only small voltage-gradients, or which may be regarded as equipotential. If this condition holds, the voltage distribution of the insulator itself remains almost unaltered, and therefore the flashover characteristics and factor of safety may be only slightly affected. It seems, therefore, that one might design an insulator with corrugations which would form equipotential surfaces and use such corrugations to shield other parts of the insulator from projected deposits, particularly those formed from sea salt, thus leaving comparatively clean those surfaces along which the potential drop is great. This condition has been shown in the laboratory to be possible, and I submit it to the authors for their consideration. In such experiments a conducting paint could be used to simulate the deposit.

There is no doubt that it may be possible on an insulator to provide some form of protection by metal shields, but in formulating a design one must obtain value for space otherwise the insulator will have disadvantages in other directions such as will reduce or possibly prohibit its application in industry. On this assumption one might criticize the very tall insulator shown in Fig. 10, and ask whether it would not have been possible to provide an extra porcelain shed taking up rather less height and which would have served the same purpose as the metal disc in affording protection against the effect of mists and deposit, at the same time providing a higher insulation value for normal working conditions. It would be interesting to have wet-flashover and impulse test data for the P.9 insulator. The foregoing assumes that the purpose of these investigations was to solve the industrial problem and eventually to find an insulator of practicable size which would meet the deposit conditions without undue sacrifice of the normally required characteristics.

The authors may be interested to note that after heavy discharges have occurred on insulator surfaces between patches of damp or streaky deposit, e.g. sea salt, the porcelain glaze loses its glossy appearance and acquires streaks of a matt appearance. The same effect can be reproduced on glass, and when examined under a microscope the dull parts of the surface appear as a series of minute cracks. When heavy discharges are taking place between patches of conducting material such as salt, carbon, or oil-smoke deposit, they are usually yellow in colour and afterwards one may find the marking on the insulators where the discharge has taken place, a condition which causes progressive destruction of the glaze.

A further point of possible interest is the change of voltage distribution on multi-unit suspension strings as a result of their being immersed in ordinary mist or that formed by sea water. With normal capacitance voltage distribution the units nearest the line usually take more than their share of the total voltage to earth, but the effect of mist in producing a resistive leakage path across each insulator is to reduce the voltage across the line unit by an amount depending upon the density and resistivity of the liquid from which the mist is formed, so that increased proportions occur on units higher up or nearer the unit connected to earth. It would be interesting to know whether the authors have noted a similar effect due to the formation of dew.

Mr. V. Pereira-Mendoza: It would appear that dew formation on insulators is dependent on the air being saturated with water, on there being a temperature-difference between the air and the insulator, and on the insulator being able to radiate heat to surrounding objects. One would have expected to find in the paper details of (*a*) the humidity of the air (to make sure it was saturated), (*b*) the temperature of the air surrounding the insulator, and (*c*) the temperature and nature of the surrounding objects. As none of these details are given it would be difficult to repeat the experiments which the authors have conducted. It is not surprising in the circumstances that they obtained such diverse results as are given in Table 2. The reason for the great divergence shown, for dew deposits corresponding to 1·8-kW dissipation, may be that the air surrounding some parts of the insulator was not completely saturated, so that, instead of a heavy dew deposit occurring, the salt would merely become damp owing to the hygroscopic absorption of the magnesium chloride. In this case, one would have two different conditions, depending on whether the insulator was covered with dew or was merely absorbing moisture from the atmosphere.

Another point which occurs to me is that moisture might well condense on the top baffle plate, and thence drip down on to the insulator, forming quite large streams of water on the top shed.

Perhaps I might describe the method of obtaining a humid atmosphere which is used in the Manchester College of Technology. The insulator is tested in a chamber about 6 ft. cube, composed largely of glass. Humidity can be obtained by means of two streams of air coming from two vessels, one of which contains heated

water and the other granulated calcium chloride. By regulating these two streams and also the temperature of the water, one can obtain any degree of humidity between 24 % and saturation. The humidity is maintained constant throughout the chamber by agitating the air with a fan, and by the use of baffle plates. I should be interested to know what is the nature of the authors' latest apparatus for producing humidity.

Dr. J. L. Miller: I would ask the authors whether they have considered the question of the reduction in impulse flashover voltage of an insulator like that in Fig. 7 when the proposed metal shield is in position. An excessive reduction would, of course, bring the impulse flashover voltage within the range of switching surges.

Regarding the question of industrial deposits, several years ago we suitably sprayed some 132-kV insulators so that with full power-frequency voltage across them there was considerable local sparking accompanied by the usual sizzling noises; in fact, the insulators were on the point of flashover. It is interesting to record, however, that despite these apparently severe conditions there were no appreciable surges in the windings of a large transformer connected to the busbars supported by the insulators—a question frequently raised by operating engineers. I am not in a position to say now whether the conditions we obtained at that time approximated to those occurring in practice with bad industrial pollution; and while my own opinion, based on other work and on researches like those described by Messrs. Melsom, Arman, and Bibby,* is that insulators which are badly polluted do not give rise to transformer stresses of any worth-while magnitude, nevertheless it would be interesting for the authors at some future date to check our findings, using their new "pollution production" technique.

Radio interference from polluted insulators is another interesting problem, and from measurements made in the field I have found that even a sparking insulator on a high-voltage line does not necessarily give rise to serious interference. I have no information, however, on the effect of insulators which are sparking badly, and I should therefore like to know whether the authors have any such experience.

Mr. G. H. Sammons: Mr. Bell's point about the cleaning of the insulators is a very sound one; everything that has to be cleaned should be so designed that it can be easily cleaned, and the easiest way of cleaning insulators is by means of rain. In some grid substations a hosepipe is used for cleaning insulators, and in the U.S.A. insulators are often changed while the line is alive.

Have the authors made any inquiry of the insulator manufacturers as to the difficulties likely to be met in manufacturing the insulators with metal skirts. How long will the metal skirts last in a salty or sulphurous atmosphere?

The authors claim to have experimented with all types and shapes of insulator, but they do not mention experiments with glass insulators. These should certainly be included in their further experiments, as I think that in the future much more will be heard of them.

Mr. F. W. Taylor: The question of leakage over the surface of an insulator is very important to the power engineer, but to the testing engineer it is even more important, since the magnitude of the leakage currents may determine whether he can test a line or whether he must wait until more favourable conditions occur.

From Table 4 it is evident that a voltage to earth of twice the normal value would produce a leakage current over each insulator in excess of 50 milliamp. This means that if alternating current is used to test the line the kVA required will be increased from 50 % to 100 % above the normal charging kVA of the line, and if it is intended to use direct current the test will have to be postponed until the leakage current per insulator is considerably less than 50 millamp., i.e. of the order of 1 milliamp. per insulator. It is therefore very interesting to note the number of leakage-current measurements made during the tests carried out by the authors. Could they, from their experience with the arrangement shown in Fig. 15, provide a table giving the leakage current on some standard insulators under salt and smoke deposit conditions with varying degrees of humidity? This would be very useful information, as it would give the testing engineer some idea as to whether it is of any use trying to carry out a test under a given set of weather conditions, without the necessity of taking the testing equipment to site to find out.

The bulk of the current will, of course, flow when the voltage wave is a maximum, either positive or negative, and will probably be considerably more with d.c. than with a.c. testing. If the authors have taken any oscillograms of the leakage current over any of the insulators mentioned I should like to see one included in their reply, if possible with an estimate of the leakage current under constant d.c. voltage of the same peak value. If the authors cannot give this information, or it is subject to too many variables, I suggest that the idea might be used as a future line of research.

* *Journal I.E.E.*, 1930, vol. 68, p. 1476.

THE AUTHORS' REPLY TO THE DISCUSSIONS

Prof. W. J. John and **Dr. C. H. W. Clark** (*in reply*): Much of the discussion has centred round the new type of insulator described in the paper and known as Type P.9. Mr. Marshall, Dr. Miller, and others mention its impulse flashover voltage. Under normal conditions this would be normal, although the insulator is much longer than an ordinary one with the same flashover voltage. Under severe weather conditions when the unprotected part of the insulator had become useless the impulse flashover voltage would be low. In its present form the insulator would then stand surges, such as those due to switching, up to 3 times the working voltage, but would fail under lightning. If there is a high probability of lightning during dew or fog this aspect requires careful attention.

Many speakers mention the possibility of trouble due to birds; the probability of such trouble seems to us to be exaggerated. The P.9 insulator, above the metal skirt, is a normal 33-kV insulator, and if a bird settles on the disc in dry weather and touches the cylinder it

will get a slight shock due to the capacitance current from the conductor to the cylinder (this, incidentally, will probably deter it from building a nest there). The upper part of the insulator, however, will take the full line voltage with no risk of flashing over. Only under conditions in which a normal insulator would fail will the possibility of trouble due to birds exist. While this consideration shows that the probability of bird trouble is lower than many speakers suggest, some form of bird guard or some modified shaping of the disc to make it less inviting as a perch for a bird is desirable.

The possibility of damage due to the power arc following a lightning flashover must be guarded against. This might be accomplished by the use of a vertical arcing horn on the cross-arm. Such an arrangement has already been suggested as a means of making the positive and negative impulse flashover voltages of a pin insulator equal, in order to assist in the co-ordination of line insulation.* It would probably be possible to combine the functions of bird guard and arcing horn.

It is doubtful whether, as some speakers suggest, any material other than metal would be better for the cylinder, but Mr. Standring's suggestion that the disc should be placed under an insulator which has a deep under-shed but to which no separate cylinder is attached seems a good one. It might still be necessary to provide an arcing horn on the cross-arm.

The use of the leakage-current surges as a criterion for judging an insulator's performance under deposit conditions is now well known, but has aroused some criticism. In our opinion it is a better indication of the factor of safety of an insulator than is a measurement of the flashover voltage. It has the advantage that the test can be carried out at the working voltage and can be continued long enough to take account of the time factor, which our tests have shown to be very important. The speed of raising the voltage in a dry-flashover test is not very important; when a certain voltage is reached flashover takes place, probably in a few microseconds. In tests in dew on a dirty insulator, flashover is led up to by a series of discharges; the severity of these discharges gradually increases and, when they become extensive enough, a condition which is indicated by current surges of about 100 milliamp., flashover finally occurs. The process of drying-off some parts of the surface and accumulating more moisture on other parts, resulting in heavier and more extensive discharges which finally develop into flashover, may take 10 or 20 minutes. The test should therefore be continued for at least 30 minutes at a constant voltage to see whether the insulator will flashover. If it does not, the leakage-current surges show how near it came to flashover.

Mr. Marshall's remarks concerning leakage losses are interesting. The laboratory tests showed that Type P.9 has a negligible leakage current under all conditions. In this it differs completely from all normal insulators. It will be interesting to see the results of tests on the corrugated cylinder type of insulator which Mr. Marshall mentions. The same insulator might be developed from Types P.7 and P.8 of Fig. 6 if the intermediate metal fittings were left out. The good performance of P.7 and P.8 indicates that good results may be obtained with the cylindrical type.

* T. E. ALLIBONE: *Journal I.E.E.*, 1937, vol. 81, p. 747.

The neglect on our part to include in the paper the anti-fog design shown in Fig. A by Mr. Marshall is regrettable—it was a pure oversight. We agree with Mr. Marshall that the British development of anti-fog insulators is a notable achievement.

We cannot entirely agree with Mr. Harris concerning the best shape for an insulator. Insulators which have been successful in industrial-deposit conditions have so far been of simple design, to facilitate natural cleaning, while those which have given good performance in salt-deposit conditions have been complicated, to provide the maximum screening. Insulators for the two conditions are therefore of opposite types, and it appears that a radically new principle must be introduced to cope with both conditions at once.

We are in complete agreement with Mr. Ryle's opening paragraph. We do not claim that a perfect technique has been developed in the paper; since the paper was written several notable modifications have been made as the result of further work. We do believe, however, that along the lines indicated in the paper will a satisfactory solution be eventually developed. A suspension-insulator unit has been designed (on paper) using the same principle as P.9, but has not been manufactured. Mr. Ryle's remarks concerning test gantries are of interest, and more information on the points he raises is very desirable. In this connection the remarks of Mr. Forrest and of Prof. MacGregor-Morris, Mr. Langton, and others are of interest.

We agree with the conclusions of Mr. Standring, and would refer him to Mr. Cameron's contribution to the discussion for information regarding the effect of steam in raising the temperature of the lower parts of the insulator.

Mr. Forrest's remarks are of particular interest, based as they are on unique practical experience of insulator behaviour. The use of leakage-current surges as the criterion of insulator performance is an important advance in the technique of testing under deposit conditions, for which we must thank Mr. Forrest. Our own tests showed that, under given conditions, the frequency of the surges was not as important as their magnitude. We think Mr. Forrest will agree that in tests such as he has carried out, where insulators are exposed to continually varying natural conditions, the number of surges in a given time is a measure of the minimum severity at which surging starts. The leakage current of a bad insulator surges while the severity of the weather conditions exceeds a certain level, that of a better insulator only while the severity exceeds a higher level, i.e. during a shorter fraction of the total time. If this view is correct, the frequency of the current surges is important in long-duration tests under varying conditions, while in tests under controlled conditions such as the laboratory tests described in the paper it is only necessary to measure the magnitude of the surges.

Mr. Cameron's remarks embody the results of recent research and certainly indicate that the method of dew formation requires further careful research. We accept his criticisms, and agree that the explanation he gives of certain anomalies is probably correct.

In reply to Mr. Gillam, no tests have been made with an insulator completely shrouded in metal.

Mr. Burton's statement that leakage-current surging is severe under light rain conditions agrees with our experience. We found this to be so only if the rain was accompanied by mist. We note with interest his account of the use of shields.

As suggested by Mr. Broughall, the laboratory salt-testing technique might also be used in experiments on the life of pins. Prof. MacGregor-Morris's contribution is particularly interesting. His work in connection with the measurement of wind velocity is well known, and the phenomenon he mentions is certainly of interest in relation to the present research.

Mr. Jeffcock raises a number of important points concerning radio interference caused by insulators. This problem is being studied at Queen Mary College, where an interference-measuring apparatus is now being used in connection with the insulator tests. There exists a recognized procedure for carrying out such tests. We welcome the suggestion to work in close collaboration with the General Post Office and with the Central Electricity Board.

The observations of Mr. Andersen are of interest. It is well known that low capacitance can assist in reducing radio interference on a dry insulator. Whether this is so in the more complicated case of deposits can be shown by actual tests. We agree with Mr. Dixon that the high-frequency aspect is of great interest in connection with insulator problems.

Dealing with Mr. Fennell's valuable contribution to the discussion, we note with particular pleasure the statement that the " brine machine " produces crystals similar to some he has found in practice, because the machine has been criticized on the ground that it produces too much salt on the insulator being tested. We are now of the opinion that it may produce more salt than occurs in the majority of brine storms, but that it gives a fair reproduction of what occurs in a very bad storm such as that described by Mr. Fennell.

We believe that brine conditions are the worst that can occur, and we agree that an insulator designed to withstand brine and a moderate industrial deposit should prove to be satisfactory for general use in Britain, although different designs might be necessary for many districts. The suggestion that a design intermediate between P.6 and P.4 should be standardized has much to commend it.

The surface-resistance coefficient is not so difficult to measure as Mr. Fennell imagines. Approximate methods are available which reduce the amount of labour involved. The surface-resistance coefficient is undoubtably better than the leakage distance as a criterion of probable insulator performance. Several of the suggestions made by Mr. Fennell are being followed up in the work which is now proceeding.

Mr. Mansfield gives some interesting data of insulator performance. We agree that for salt deposits shielded surfaces are essential. Particularly interesting is the point that salt deposits do not appear to be cumulative.

We agree with Mr. Davies that dew is an important factor affecting insulator behaviour, and work is now proceeding to investigate the effect of different methods of dew formation. Merely to moisten a deposit is not sufficient—the method of moistening it is important. Regarding surface-resistance coefficient, this is a helpful guide to the performance of insulators of similar shape, but must not be used to the exclusion of other considerations. In our opinion it would be unwise to try to give a definite figure for the surface-resistance coefficient which would ensure satisfactory operation even under stated conditions.

In reply to Mr. Holttum, the ideal is, of course, an insulator which never requires cleaning. If this ideal is not attainable the periods between cleaning should be made as long as possible. There are substations where the insulators are cleaned every day; if the period between cleaning could be lengthened to a year this would effect a great saving. The difficulty of cleaning P.9 insulators is, however, a serious criticism, and the cylinder must be made easily detachable.

The oscillograms of Figs. 5 and 11 are of leakage current on a voltage base, as described on page 594.

Mr. Langton has drawn on his wide experience in his contribution to the discussion. We agree that for salt desposits ribbing of the under-surfaces is necessary; our investigations showed, however, that ribbing has a detrimental effect on the performance in regard to industrial deposits. Mr. Langton seems to assume that one can judge the performance of an insulator under industrial deposits by its performance in regard to salt. This is not so. We agree that if the suspension insulators shown in Fig. 14 had been tested in the wind tunnel very different results from those shown in Fig. 8 would have been obtained. Type 1 with its ribbed undersurface would probably have given a better performance than the types without ribs. In industrial districts, however, Type 1 has had to be discarded and types such as 2(*b*) and 4 are giving greatly improved performance.

As regards the fact that flashover at working voltage was not obtained in the laboratory tests, this was, we believe, due to the high impedance of the testing transformer. We point out in the paper that transformers for deposit tests must have a much lower impedance than that permissible for measuring dry or wet flashover voltages. The work is being continued, and in this connection insulators are being erected near the sea coast to enable observations to be made of their behaviour over long periods.

Mr. Perry confirms the views of other speakers that test sites may not reproduce line conditions. In the laboratory tests the insulator was mounted on a cross-arm so that any shielding which might be obtained from this in service was imitated. The pole would shield the insulator only from winds from one direction. The term " leakage-current surge " is used in the paper to indicate a sudden increase in the leakage current as measured by a milliammeter, and not the surges shown on the oscillograms, which last for a fraction of a cycle only. As regards the best shape for an insulator for salt deposits, insulators P.6, P.7, and P.8 all have the characteristic of extensive ribbing on the under-surfaces. This we consider essential if a good performance is to be obtained under salt conditions. In addition, P.7 and P.8 subdivide the total voltage, thus reducing the voltage on each part. We

agree with Mr. Perry's conclusions concerning the testing of insulators under industrial deposits.

We also agree with Mr. Bell as to the difficulty of reconciling the results of laboratory and field tests. Such reconciliation will only be obtained by long investigation of the factors operating in both cases.

We agree with Mr. Farrer concerning the difficulty of forming industrial deposits artificially. The main basis of comparison used in our tests for both the suspension and the pin-type insulators was the magnitude of the leakage-current surges. The difference in behaviour of the ribbed and non-ribbed insulators in the two tests is due to the different effects of salt and industrial deposits.

We discuss in the paper the effect of dew deposits on the voltage distribution over an insulator; in our opinion the instability of voltage distribution which occurs under these conditions is the first step towards the failure of the insulator.

In reply to Mr. Pereira-Mendoza, the object of the dew test described in the paper was to ensure that the humidity was 100 %, and that the insulator was cooler than the surrounding air. We certainly obtained a copious dew formation always, but we agree that the conditions could not be exactly described. It is hoped to publish a description of a better method of dew formation later. We refer Mr. Pereira-Mendoza to Mr. Cameron's contribution to the discussion.

Dr. Miller's suggestion of testing to see whether voltage surges are set up in transformer windings during bad weather conditions is worth investigating. It seems probable that, in view of the comparatively small magnitude of the leakage-current surges, the voltage surges would not be serious even if surges occurred simultaneously on a number of insulators.

Mr. Taylor raises an entirely new aspect of the subject in his reference to line testing. We presume he is referring to acceptance tests and suppose that these would be carried out on new lines where the insulators are comparatively clean. In the case of a line near the sea, however, the insulators might be dirty, since salt deposits form rapidly. In such a case we suggest that the testing engineer selects either a very dry day or one just after rain, which will have washed the insulators clean. We would refer Mr. Taylor to Mr. Forrest's remarks on the impracticability of carrying out live-line tests if the humidity exceeds 70 %.

THE DIELECTRIC CHARACTERISTICS OF A CHEMICALLY PURE SYNTHETIC RESIN*

By C. G. GARTON, Associate Member.†

(*Paper first received 7th March, and in revised form 10th May, 1939.*)

SUMMARY

The present work gives the results of measurements of the temperature variation of the dielectric constant, loss angle, and conductivity, of a sample of chemically pure glycol-phthalate resin. The effects of known amounts of impurity are investigated. It is shown that the conductivity obeys accurately an inverse exponential law of temperature. The dielectric constant and loss angle follow qualitatively, but not quantitatively, the Debye equations for a polar material. The cause of this discrepancy is discussed, and a résumé given of the behaviour of other types of polar material, of which six classes seem to be distinguishable.

A brief indication is given of seven possible modifications of the Debye theory, not involving a distribution of relaxation times, which have been investigated and shown to be unsatisfactory. It is concluded that a distribution of relaxation times is, of those considered, the only possible hypothesis consistent with observation, and a quantitative expression for the loss angle is worked out and shown to agree well with observed data. The results show that the viscosity to dipole rotation follows the same law of temperature variation as the d.c. resistivity.

Appendices give the method of preparation of the chemically pure resin; the circuit of a 50-kc./sec. bridge which has been found simple and convenient for this work; and the computation of an integral which occurs in the prediction of the loss angle and seems not to have been previously computed.

CONTENTS

* The Papers Committee invite written communications, for consideration with a view to publication, on papers published in the *Journal* without being read at a meeting. Communications (except those from abroad) should reach the Secretary of The Institution not later than one month after publication of the paper to which they relate.

† British Electrical and Allied Industries Research Association.

(1) INTRODUCTION

The object of the present work is to investigate the dielectric characteristics of a synthetic resin which is as nearly as possible chemically pure, from the following points of view.

(i) Comparison with the known characteristics of industrial resins.

(ii) The question whether a resin free from polar impurities would display polarity.

(iii) The electrical effects of small quantities of known impurities.

(iv) The question whether the polar characteristics, if present, would obey the simple Debye equations; and, if not, to investigate the modifications required in the Debye theory as applied to amorphous solids.

(2) EXPERIMENTAL MATERIAL

The resin chosen consists of an equi-molecular condensation product of ethylene glycol with phthalic anhydride, and may be called glycol phthalate.‡ This resin was chosen as the experimental material because it is one of the simplest of the synthetic resins, and because it does not polymerize to an infusible form, so that the condensation and subsequent purification can be carried to completion. It does not change its properties by polymerization during measurement.

(3) EXPERIMENTAL RESULTS

(a) Dielectric Constant and Loss Angle

The values of the dielectric constant (κ) and of tan δ (δ = loss angle) were measured upon samples of the pure resin at 50 cycles per sec. and 50 kc./sec., and upon samples containing 2 % of free glycol and of free phthalic anhydride respectively at 50 kc./sec.

The samples were cast from the molten resin by pouring into an electrode system comprising two circular aluminium electrodes with an active diameter of 6 cm., spaced 0·5 mm. apart by three small quartz spacers. The system was provided with a guard ring, and completely screened. For measurements at 50 cycles per sec. a standard type of Schering bridge was used, and for measurements at 50 kc./sec. the bridge described in Appendix III. Measurements were made at a stress of approximately 500 volts per mm. at 50 kc./sec., and 1 000 volts per mm. at 50 cycles per sec., but the results were completely independent of stress in this region.

The results obtained on the pure resin are shown by the curves of Figs. 1 and 2, and the results on the samples containing impurity are recorded in Fig. 1 as separate points.

‡ For information as to the properties, preparation, and rate of condensation of this resin, see Reference (1); and for the preparation of the specially pure sample used in this work, see Appendix I.

(b) The "Static" Dielectric Constant

It is probable[17]* that the results obtained in d.c. measurements of the dielectric constant of polar substances depend very largely upon the technique of measurement, the dipoles being capable of slow orientation over periods of many minutes, or even hours. The results given in this Section must be considered with this fact in mind. The results were obtained by charging the sample, of pure resin, in the electrode system already described, to a d.c. voltage of 300 volts, and discharging it through a galvanometer with a period of 2 sec., previously calibrated with a known air condenser. The results are shown in Fig. 2.

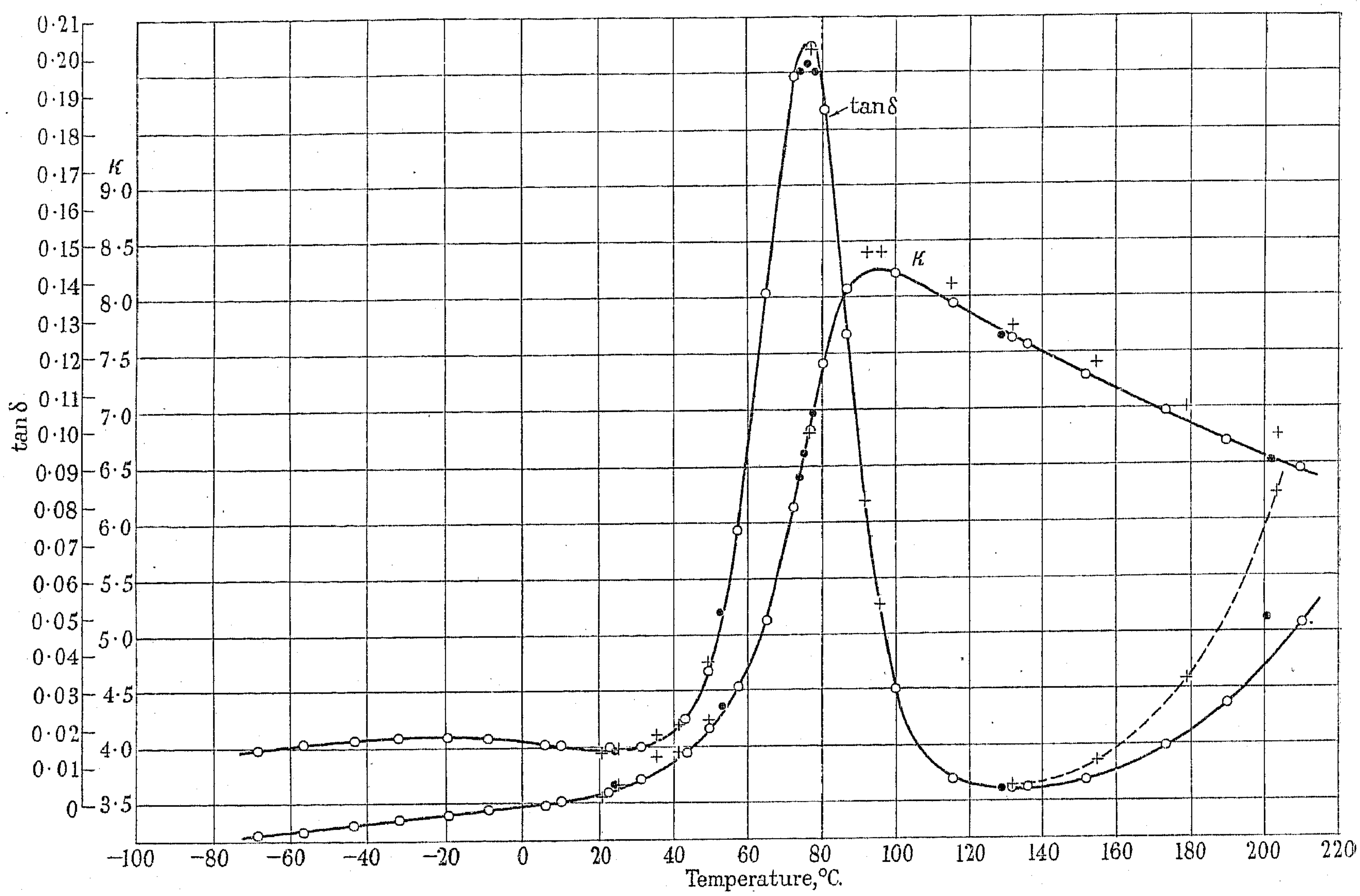


Fig. 1.—Variation of κ and tan δ with temperature at 50 kc./sec.

○ Pure glycol phthalate.
+ Glycol phthalate plus 2 % phthalic anhydride.
● Glycol phthalate plus 2 % ethylene glycol.

(c) D.C. Conductivity

To determine the effect of impurities upon the direct-current conductivity of the resin, conductivity measurements were made upon samples of the pure resin and upon samples of the resin containing 2 % of free glycol and free phthalic anhydride. The measurements were made by means of a sensitive galvanometer in series with the sample, using the electrode system already described. The d.c. voltage varied from 650 volts for the lower temperatures to 45 volts for the higher. This reduction was necessary to avoid excessive current and breakdown of the sample. No dependence of the results upon voltage was observed unless the voltage was reduced to a few volts, when the apparent resistance increased, owing to the existence of a polarization voltage of about 0·5 volt. At 45 volts the error was quite negligible. At the higher temperatures, the decrease of current with time was considerable. For example, at 184° C. the current fell to half its original value in 8 minutes, after which the rate of fall was very slow. As the conduction loss under a.c. conditions depends not on the final conductivity but on the conductivity after a time comparable with 1 cycle, the current was measured as quickly as the swing of the galvanometer would permit, which was about 2 sec. after switching on.

The results are shown in Fig. 3, in which the curve refers to the pure resin and the points to the samples containing impurity. The abscissae of Fig. 3 have been plotted in terms of the expression $100/(T - 253)$, where T is the absolute temperature, to show the agreement between the experimental results and an empirical formula derived in the next section of the paper. Since the variation with impurity is very small compared with the temperature variation, the results cannot be adequately represented by curves. Sample results are there-

* The index numbers in the text refer to the list of References (see page 634).

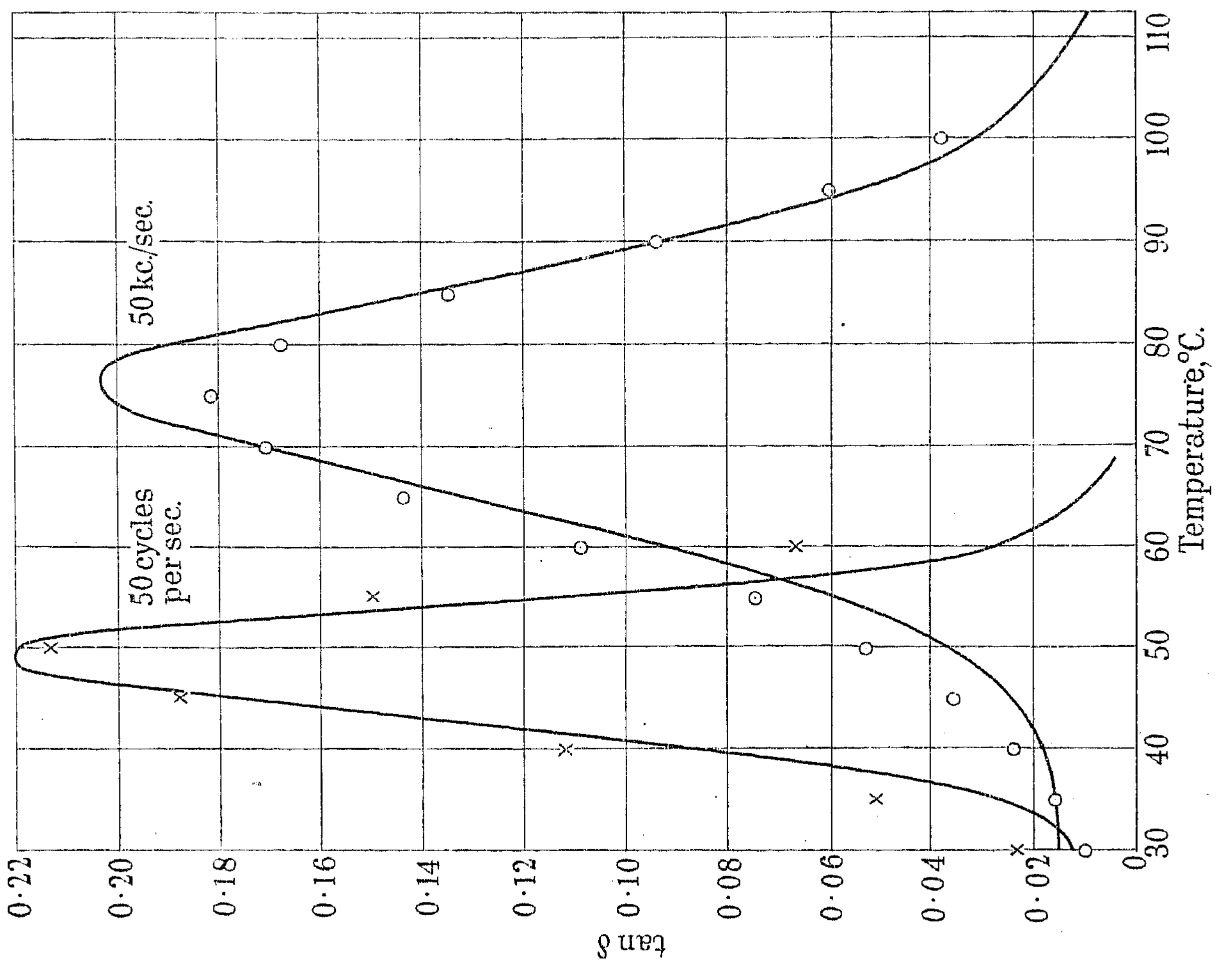


Fig. 7.—Comparison of observed and calculated variation of tan δ with temperature at 50 cycles per sec. and at 50 kc./sec.

Curves.—Observed values.
Points.—Calculated values.

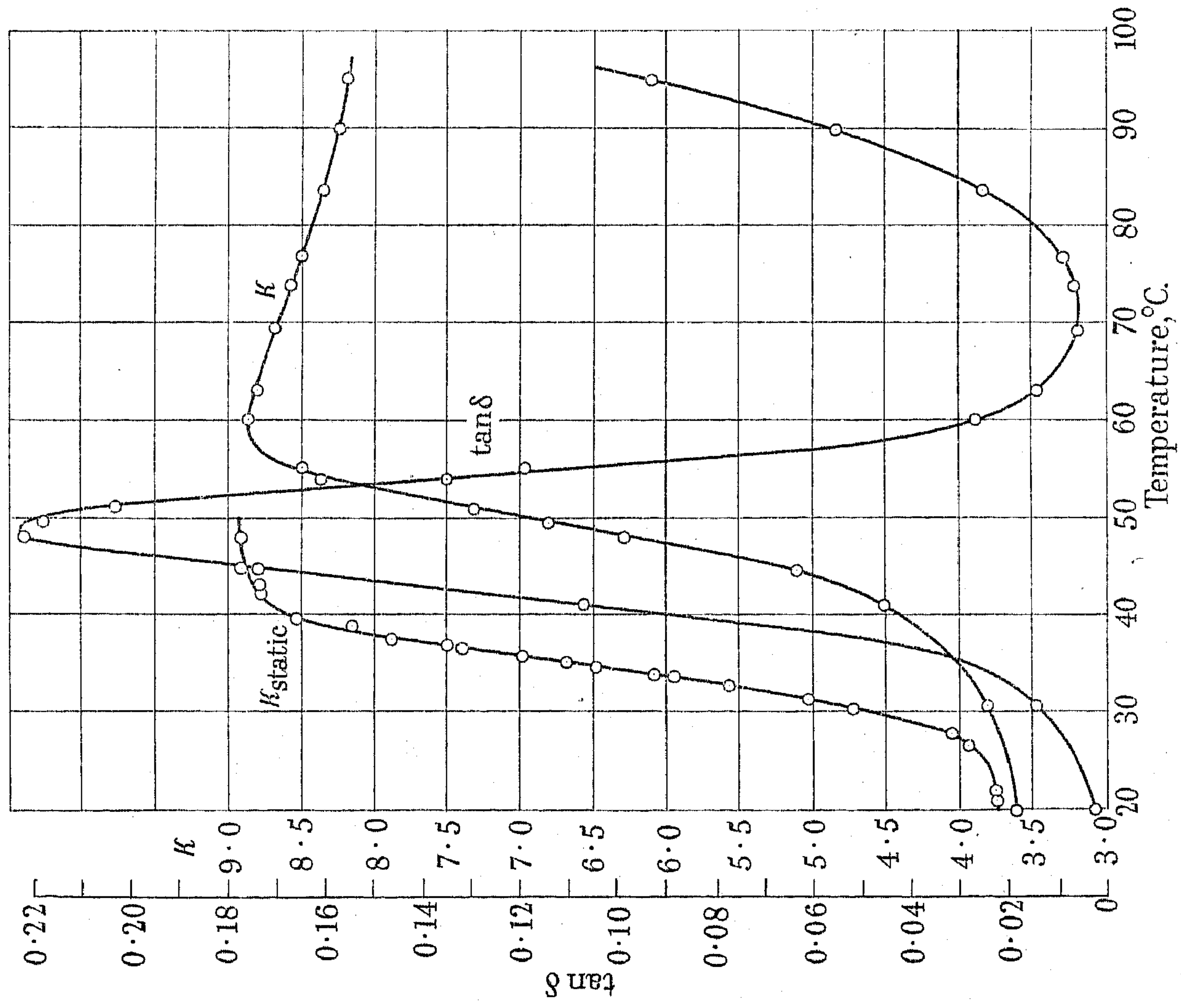


Fig. 2.—Variation of κ and tan δ with temperature at 50 cycles per sec. and "static" dielectric constant.

fore also given in Table 1, where $\log R$ is the common logarithm of the resistivity in ohms per cm. cube.

Table 1

Temperature, ° C.	log R	Temperature, ° C.	log R
Pure resin			
61·7	13·279	145·5	9·265
83·3	11·651	170·8	8·730
98·4	10·863	210	8·188
122·0	9·930		
Resin plus 2 % free phthalic anhydride			
55·6	13·778	134	9·301
68·3	12·553	157·5	8·710
85·5	11·375	199	8·008
100	10·607		
Resin plus 2 % free ethylene glycol			
55·6	13·778	136·7	9·283
71·2	12·262	167·5	8·606
86·0	11·328	192·3	8·233
109·5	10·158		

(4) DISCUSSION OF RESULTS

(a) Conductivity

The results (see Table 2) show that the conductivity of the pure resin is low compared with that of other resins of only technical purity, which were measured for comparison.

It is interesting that glyptal, chemically very similar to glycol phthalate, has 30 times lower resistivity than the latter, even after 25 hours' polymerization. This is doubtless due to the impossibility of taking the reaction to completion in a material which polymerizes.

Table 2

Material	log R at 100° C.
Pure glycol phthalate	10·79
Pure glycol phthalate plus 2 % phthalic anhydride	10·58
Shellac	9·33
Glyptal after 6 hours' polymerization at 175° C.	6·40
Glyptal after 25 hours' polymerization at 150° C.	9·30

The conductivity of the pure resin is increased by addition of impurities, but to a much less extent than was expected. Thus 2 % of either glycol or phthalic anhydride decreases the resistivity by at most 40 % of its original value.

(b) Variation of Resistivity with Temperature

A relation between temperature and resistivity which is frequently proposed is

$$\log R = A + \frac{B}{T}$$

where A and B are constants, and T is the absolute temperature. This relation fits the results of Fig. 3 very badly.

P. P. Kobeko and E. V. Kuvshensky,[3] and other investigators, have proposed to measure the temperature not from absolute zero but from some value T_0 which is a characteristic temperature for each substance. The relation then becomes

$$\log R = A + \frac{B}{T - T_0}$$

Kobeko and Kuvshensky[3] use an approximation to this equation which also does not fit the data of the present work.

Upon using the exact form of the equation, however, and determining the constants A, B, and T_0 to fit the three points $\log R = 9$, 11, and 13, it is found that the data fit the equation very accurately. The constants require the values

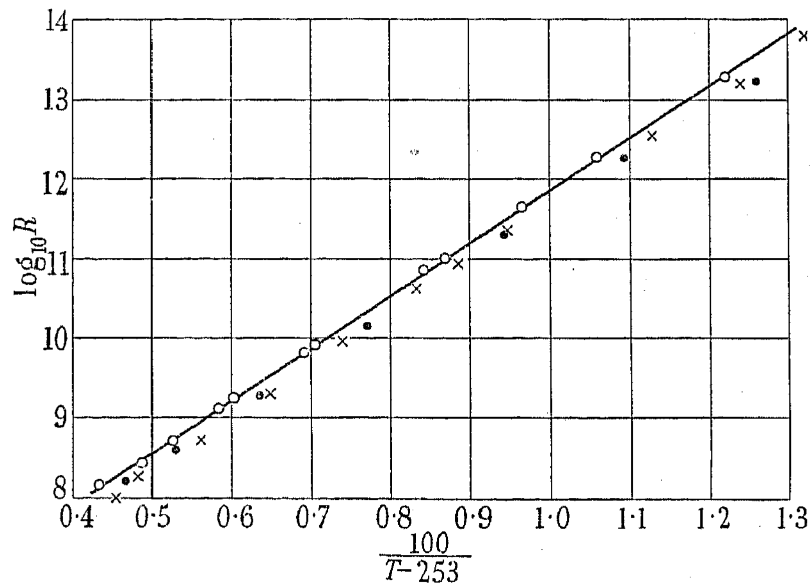


Fig. 3.—Variation of resistivity with temperature.
○ Pure resin.
× Resin plus 2 % phthalic anhydride.
● Resin plus 2 % ethylene glycol.

$$\log R = 5 \cdot 3 + \frac{657}{T - 253}$$

Fig. 3 shows this relation plotted in the form of a straight line with a scale of $100/(T - 253)$ as abscissae. The points represent the experimental data and the fit between them is remarkably good. Two other possible relations were investigated, but neither gave so good agreement as the above.

It is not known whether the constant 253 in this equation, representing a temperature of − 20° C., has any physical significance. According to the equation, the resistivity would become infinite at this temperature. Presumably the equation ceases to be true at some higher temperature, although it may be noted as possibly significant that the 50-kc./sec. loss-angle curve shows a secondary maximum precisely at − 20° C. It would be interesting to attempt to measure the resistivity in this temperature region by a more sensitive technique, and also to measure the static dielectric constant in the same region by the technique of very slow charge and quick discharge developed by P. P. Kobeko.[17]

(c) The Dielectric Constant and the Loss Angle

The curves of dielectric constant and loss angle of the resin show in general the shape predicted by Debye. Outside the Debye region, the loss angle rises again at very high temperatures. This is already well known to be due to conductivity losses. The very low minimum of loss angle ($\tan \delta = 0\cdot003$) between the Debye and the conduction regions indicates that no appreciable third source of loss is present.

The addition of impurity affects the results only when the conduction loss is important. In the polar region of the curves the pure and impure samples give almost identical results, showing conclusively that the polarity is a property of the resin itself.

The small secondary maximum at low temperatures remains unexplained. In the course of other (unpublished) work a similar secondary maximum at temperatures below zero has been found in shellac and polymerized glyptal, but not in rosin nor in unpolymerized glyptal. The fact that some materials, with an identical technique of measurement, fail to show the effect, indicates that it is not a spurious effect connected with the refrigeration of the sample. P. P. Kobeko[19] suggests that this maximum is connected with an alteration in the structure of the material, but the experimental evidence on this point is inadequate.

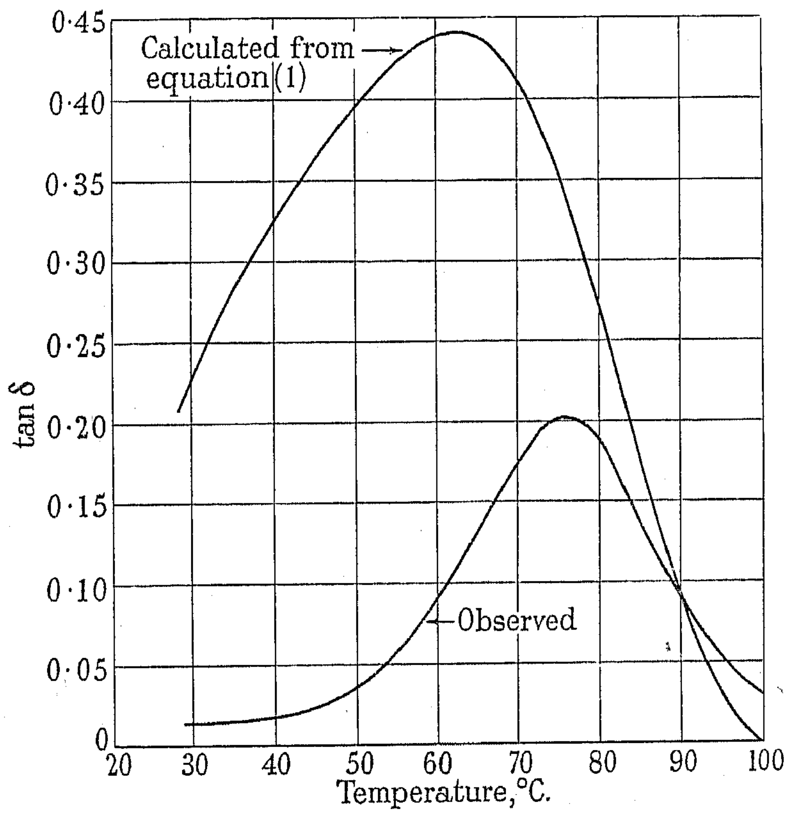


Fig. 4.—Comparison of observed values of $\tan \delta$ with values calculated from the simple Debye theory, for 50 kc./sec.

Although the experimental data are in general agreement with Debye's theory, there is no quantitative agreement. As is usually found with amorphous materials, the maximum value of the loss angle is much lower than that predicted, and occurs associated with too high a dielectric constant.

A knowledge of the " molecular viscosity " as a function of temperature is necessary in order to predict the shape of the dielectric-constant and loss-angle curves in their entirety, but two relations can be obtained without such knowledge. If κ_0 and κ_∞ be the values of the dielectric constant above and below the Debye region respectively, and κ be the value at any intermediate temperature, then

$$\tan \delta = \frac{1}{\kappa}\sqrt{[(\kappa_0 - \kappa)(\kappa - \kappa_\infty)]} \quad . \quad . \quad (1)$$

which passes through a maximum when

$$\kappa = \kappa_m = \frac{2\kappa_0\kappa_\infty}{\kappa_0 + \kappa_\infty} \quad . \quad . \quad . \quad . \quad (2)$$

and the value of $\tan \delta$ is then

$$\tan \delta\,(\max) = \frac{\kappa_0 - \kappa_\infty}{2\sqrt{(\kappa_0\kappa_\infty)}} \quad . \quad . \quad . \quad (3)$$

In the case of the pure resin, the lack of agreement between theory and observation is shown by Table 3 and

Table 3

Frequency	κ_m		$\tan \delta$ (max)	
	Calculated	Observed	Calculated	Observed
50 cycles per sec.	5·0	6·40	0·485	0·222
50 kc./sec.	4·9	6·65	0·440	0·204

Fig. 4. The latter compares the observed values of $\tan \delta$ with values calculated from the dielectric constant by means of equation (1). It will be seen that the agreement is very poor.

Before proceeding to discuss in detail the cause of the foregoing discrepancy, it seems worth while to mention briefly the results of other investigations into the characteristics of polar materials, in order to obtain a clear idea of the range of phenomena under discussion. Six main types of polar behaviour seem to be distinguishable from the electrical characteristics.

Table 4

	Calculated	Observed
$\tan \delta$ (max)	2·4	2·3
κ_m	5·8	6·0

The only published results dealing with solids which check accurately with the Debye theory appear to be those of Smythe and Hitchcock for ice.[4] For this substance, at 5 000 cycles per sec., $\kappa_\infty = 3\cdot0$ and $\kappa_0 = 75$, from which figures one obtains the values shown in Table 4.

Close agreement is also claimed by H. Race,[5] working with a viscous mineral oil. In this case, however, the change of κ was so small that the comparison is greatly dependent on experimental error. Moreover, k_∞ was determined by an optical method, and the value obtained may not agree with that determined by the electrical method.

In general, resins and viscous liquids give a value of $\tan \delta$ (max) equal to about half that predicted by the Debye theory, and a value of κ_m near to $(\kappa_\infty + \kappa_0)/2$.

This behaviour has been observed in a large number of substances, e.g. bakelite resin,[20] poly-chlor-diphenyls,[12] glycol phthalate (present work), rosin, glyptal, shellac (unpublished results of the author), and in many other substances by various investigators.

Smythe and Hitchcock have shown[4] that some substances with a sharp melting point, e.g. nitrobenzene, ethylene chloride, aniline, phenol, and diethyl sulphate, show a sharp fall of dielectric constant at the freezing point, and thereafter behave as non-polar or only slightly polar solids. The fall of κ is often very sharp, and is accompanied by a sharp maximum in the loss angle, often extending over only a few degrees of temperature. The explanation is obviously a " freezing in " of the dipoles, but no theory has yet been given by which the losses may be calculated.

The same investigators[6] have shown that substances of another type, e.g. HCl and dimethyl sulphate, show only a small change of κ at the freezing point, and behave as highly polar solids down to a certain transition temperature, which for HCl is at $-174°$ C., i.e. 90 deg. C. below the freezing point. At the transition temperature, κ falls abruptly, as though this were the freezing point of the material. For HCl, the fall from $\kappa = 17 \cdot 5$ to $\kappa = 3 \cdot 0$ occurs within a temperature-interval of 1 deg. C., and is accompanied by a sharp maximum in the loss angle of $0 \cdot 01$, whereas the Debye maximum for this range of κ would be $1 \cdot 0$. This behaviour has been theoretically investigated by Pauling,[8] who shows that dipoles are free to rotate in the solid state so long as their energy exceeds a value depending on their size and moment of inertia. The theory does not predict the value of the loss angle.

Hydrogen bromide[6] unexpectedly gives results quite different from HCl. The dielectric constant rises rapidly from a value of $8 \cdot 2$ at $-150°$ C. to a sharp peak of 34 at $-183°$ C., and thereafter falls rapidly. The loss angle rises to a maximum value of $0 \cdot 32$, over 30 times that of HCl. No explanation of this behaviour has been given.*

Another type of behaviour is shown by amorphous or semi-crystalline materials which either do not melt or are far below their melting points. For these substances, e.g. cellulose and cellulose acetate,[7] the variation of κ and $\tan \delta$ with temperature is very slow, extending over some tens of degrees of temperature. Similar flat maxima are also shown by some resins at temperatures much below their normal Debye maximum, e.g. by shellac, glyptal, and glycol phthalate, as discussed above. It is unlikely that this behaviour is due to small quantities of impurity as the associated change of κ is quite large (from $3 \cdot 5$ to something less than $3 \cdot 2$ in the case of the very pure glycol phthalate). It may be due either to non-uniformity of structure, giving an average result over a wide temperature range, or to the fact that the molecular structure of the material changes very slowly with temperature when the temperature is low.

The foregoing six types of behaviour may be summarized as follows:—

(i) Solids showing quantitative agreement with the simple Debye theory (apparently ice is the only example known).

(ii) Materials showing qualitative but not quantitative agreement (e.g. resins and viscous liquids).

(iii) Materials with a sharp change to the non-polar state at the freezing point (e.g. nitrobenzene).

(iv) Materials with a sharp change to the non-polar state at a transition temperature below the freezing point (e.g. HCl).

(v) Materials having a sharp peak in the value of the dielectric constant at a temperature below the freezing point.

(vi) Materials showing a very flat maximum in the loss-angle curve, over a wide temperature-interval (e.g. cellulose and some resins at low temperatures).

Evidently the phenomena are quite complicated if all classes of polar materials are considered, and there appears little possibility of developing a unified theory at present, except in a general qualitative way. The remainder of this paper is therefore devoted to an attempt to deal quantitatively with materials of Class (ii). Much more experimental work is required to bring out the relations between one another of the six types of behaviour which appear to exist. The literature is particularly poor in regard to measurements of the loss angle; much work records only the value of κ. It is very desirable that the loss angle should also be accurately measured in all work of this kind.

(d) Modifications to the Debye Theory

The failure of the simple Debye theory to account quantitatively for the electrical characteristics of solid amorphous dielectrics has been well known for some years, and has commonly been attributed to non-uniformity of the relaxation times of the dipoles concerned. W. A. Yager[18] has investigated quantitatively the effect of assuming a probability distribution of relaxation times, and by choosing a suitable dispersion for the distribution is able to account satisfactorily for the dielectric constant and loss angle of a number of amorphous substances. His equations are derived from the standpoint of the Wagner mechanism of loss, but will apply equally well to the Debye mechanism. The present work attacks the same problem from a different angle, particularly in that the temperature instead of the frequency variation of the dielectric characteristics is utilized. Further, no assumption is made as to the nature of the distribution function, and no disposable constants are involved. A more detailed comparison of the two methods will be made at a later stage of this paper.

Before accepting the hypothesis of heterogeneity of the dielectric, it is essential to eliminate the alternative, and more attractive, possibility that the Debye mechanism itself should be modified in its application to solids. A very detailed (and, it is believed, exhaustive) examination of this question has been made, and although the results are completely negative it is felt that they are of sufficient interest to be recorded here, as affording support by inference for the more successful theory of heterogeneity which follows. Accordingly, the following paragraphs indicate the nature and results of the various hypotheses which have been investigated, although from considerations of space all mathematical details are omitted.

(i) The omission or inclusion in the Debye equations

* Ammonium salts have very recently been discovered in this group (see R. GUILLIEN: *Comptes Rendus,* 1939, vol. 208, pp. 980 and 1561).

of the Lorentz polarization term $P/3$ is immaterial.[16] The term vanishes in any case from the final result.

(ii) Upon including the Lorentz term, but assuming that it affects only the capacitive component of the polarization, the term does not vanish, and by choosing an arbitrary coefficient instead of the Lorentz value of $\frac{1}{3}$ a correct value can be obtained for the maximum of the loss angle. The maximum is not, however, associated with the observed value of dielectric constant, and in any case the assumptions involved are highly artificial.

(iii) It was assumed that the effective resistance to motion of a dipole depends upon its orientation to the field, so that the distribution of the dipoles in angle is also effectively a distribution in relaxation time. This naturally results in values of the loss angle smaller than those given by the simple Debye theory, but still much larger than the observed values.

(iv) It was assumed that the mechanism giving rise to a relaxation time is not of the nature of a viscosity, but is due to periodic capture and release of the dipoles by inter-molecular fields strong enough to prevent (temporarily) orientation in the field until the dipole is again set free by thermal agitation. This mechanism leads to results identical with Debye's, and it is worthy of note that any mechanism whatever which leads to a differential equation of the first order, containing only one time-constant, will reproduce the Debye results, regardless of the physical nature of the mechanism.

(v) The preceding assumption was modified by assuming that the change in orientation of the dipole is proportional not (as before) to the value of the field at the moment of release, but to the change of field since the last preceding capture. This introduces a second function of time into the differential equation, and hence leads to a different result from Debye's, but one agreeing even worse with the observed data.

(vi) It was assumed that an elastic, as well as a viscous, restraint acts upon the dipoles, and that this restraint varies with temperature. It is possible to choose the elasticity as a function of temperature in such a way as to satisfy the observed data at any one frequency. For another frequency, however, the function is quite different, showing that the assumption has no physical basis.

(vii) The above assumption may be modified as suggested by A. Gemant[9] and independently at about the same time by the present author (in an unpublished report to the All-Union Electrotechnical Institute, Moscow). This modification consists in applying a relaxation time to the above elastic restraint, so that its effect becomes increasingly important with increasing frequency. This leads to the equivalent circuit shown in Fig. 5 for the dielectric. Gemant does not refer to this circuit in deriving his results, but his equations are identical with those of the circuit when $R = R_1$. This modification seems very plausible, and it does in fact lead to somewhat better results than the simple Debye theory, but quantitative investigation shows that the approximation is still very poor. The equations, of fourth degree in resistance, capacitance, and frequency, are too complicated for mathematical solution except when R_1 is zero. The solution in this case can be made to fit the observed results by choosing κ_2 as a suitable function of temperature. As in assumption (vi), however, the function holds for one frequency only, and the solution has no physical basis. If R_1 be not zero, the equations must be solved graphically, and to limit the amount of work involved some relation must be assumed between the four components of the circuit. Graphical solution shows that, if $R = R_1$ (the assumption made by Gemant), the least value of tan δ (max) is obtained when

$$\kappa_2 = \kappa_0 - \kappa_\infty$$

and this result still holds if, alternatively, it is assumed that

$$\kappa_2 R = (\kappa_0 - \kappa_\infty) R_1$$

Making this assumption, so obtaining the lowest value of tan δ (max) which Gemant's equations can give, the result is still 60 % higher than the observed value. The values of tan δ (max) are as follows: Debye mechanism, 0·44; elastic restraint, 0·32; observed, 0·20. It must be concluded that an elastic restraint on dipoles having a single relaxation time, although a very attractive hypothesis, is not adequate to explain the observed results.

It is believed that the foregoing seven assumptions exhaust the possible mechanisms for dipoles all of the same relaxation time, and since all are unsatisfactory it remains to show that the experimental results can be satisfied by retaining the Debye mechanism but assuming a distribution of relaxation times.

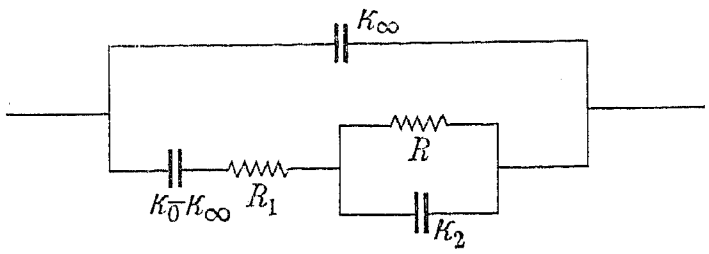


Fig. 5.—Equivalent circuit of Gemant's equations.

We make the following assumptions.

(i) That at any temperature τ there exists in the temperature-interval $\delta\tau$ a homogeneous group of dipoles having their maximum energy-loss at that temperature.

(ii) That the complete release of this group results in a contribution to the dielectric constant of $N\delta\tau$, where N is proportional to the dipolar concentration.

(iii) That each group of dipoles considered alone obeys the simple Debye theory.

(iv) That the variation with temperature of the molecular viscosity is the same as the experimentally determined temperature variation of d.c. resistivity, i.e. that the same function of temperature controls the motion of both ions and dipoles. This assumption is subsequently justified by the results.[22]

The loss due to an elementary group of dipoles ($N\delta\tau$) will vary with temperature in the same way as the loss of a circuit consisting of a fixed capacitance ($N\delta\tau$) in series with a resistance (r) which is a function of temperature; that is,

$$\delta P = \frac{(E\omega N\delta\tau)^2 r}{(\omega N\delta\tau r)^2 + 1} \quad . \quad . \quad . \quad . \quad (4)$$

where r is proportional to the d.c. resistivity R. From experiment [see Section (4)(b)], we have

$$\log_{10} R = A + \frac{657}{T - 253} \quad . \quad . \quad . \quad (5)$$

$$\therefore \quad R = K_A e^{\alpha/(T+c)} \quad . \quad . \quad . \quad . \quad (6)$$

where, for the particular resin used, $\alpha = 1\,510$ and $c = -253$. For simplicity, we eliminate the constant c by introducing a different temperature scale in which $\tau = T - 253$, i.e. a scale having its zero at $-20°$ C., and write

$$R = K_A e^{\alpha/\tau}$$

from which we assume that the resistance r can be represented by

$$r = Ke^{\alpha/\tau} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where K is a quantity defined by equation (9). Then, for any given value of temperature θ we obtain, substituting (7) in (4),

$$\delta P = \frac{\omega N \delta\tau K e^{\alpha/\theta}}{(\omega N \delta\tau K e^{\alpha/\theta})^2 + 1} E^2 \omega N \delta\tau \quad . \quad . \quad (8)$$

It may be remarked that the apparent dependence of this equation upon N is due to the fact that K also depends upon N, inversely, and that when K has been eliminated in equation (10) N appears, as it should, only as a multiplier. To evaluate K, we observe that the maximum loss occurs when

$$\omega N \delta\tau r = 1$$

where the dependence upon N is again only apparent, for the reason already given. Then if the maximum loss for the group of dipoles in question occurs at a temperature τ, we have

$$\omega N \delta\tau K e^{\alpha/\tau} = 1 \quad . \quad . \quad . \quad . \quad (9)$$

Substituting this in (8), we obtain for the loss at temperature θ, due to a group of dipoles having its maximum loss at temperature τ,

$$\delta P = E^2 \omega N \delta\tau \frac{e^{(y-x)}}{e^{2(y-x)} + 1} \quad . \quad . \quad . \quad (10)$$

where for convenience we have written $y = \alpha/\theta$, $x = \alpha/\tau$. Then the total loss at temperature θ, due to dipoles having their maximum loss distributed over a range of temperature from a to b, is

$$P = E^2 \omega \int_a^b NF(\kappa) \frac{e^{(y-x)}}{e^{2(y-x)} + 1} d\tau \quad . \quad . \quad (11)$$

where $F(\kappa)$ is a function of the dielectric constant introduced to allow for the fact that the effective capacitance of a group of dipoles will vary with the dielectric constant of the medium in which they occur, as a result of the Lorentz polarization term. It is easy to show from the polarization equation that

$$F(\kappa) = \left(\frac{\kappa_\theta + 2}{\kappa_\tau + 2}\right)^2 \quad . \quad . \quad . \quad . \quad (12)$$

where κ_θ and κ_τ are the values of the dielectric constant at corresponding temperatures.

The integral cannot be evaluated in the form (11) since N and $F(\kappa)$ are not known as functions of temperature, and even were they known or assumed the integral would probably be insoluble on account of its complexity. Resort must be had to some form of numerical solution; and we assume that an average value of N may be taken over a small temperature-interval 2β, and express the integral as

$$\tan\delta = \frac{P}{E^2 \omega \kappa} = \frac{1}{\kappa} \sum_a^b NF(\kappa) \int_{\tau-\beta}^{\tau+\beta} \frac{e^{y-x}}{e^{2(y-x)} + 1} d\tau \quad (13)$$

The solution of the integral term in equation (13) is given in detail in Appendix II. Here it is sufficient to record the result. The integral can be evaluated only if certain limits be chosen, as follows: If $\tau < \theta$,

$$I_1 = \int_0^\tau \frac{e^{y-x}}{e^{2(y-x)} + 1} d\tau = \tau \sum_{n=1}^\infty (-1)^n e^{m(y-x)} \sum_{s=1}^\infty (-1)^s \frac{s!}{(mx)^s} \quad . \quad . \quad . \quad (14)$$

And if $\tau > \theta$,

$$I_2 = \int_\tau^{-\eta} \frac{e^{y-x}}{e^{2(y-x)} + 1} d\tau = -\tau \sum_{n=1}^\infty (-1)^n e^{m(x-y)} \sum_{s=1}^\infty \frac{s!}{(mx)^s} \quad . \quad . \quad . \quad (15)$$

where $m = 2n - 1$ and provided $x >> 1$. η is an indefinitely small quantity. For the special cases when $\tau = \theta$,

$$\left.\begin{matrix} I_{01} \\ I_{02} \end{matrix}\right\} = \tau \left\{ \frac{\pi}{4x} \mp \frac{1 \cdot 834}{x^2} + \frac{5 \cdot 8}{x^3} \mp \frac{23 \cdot 7}{x^4} \ldots \frac{s!}{x^s} \ldots \right\} \quad (16)$$

the upper signs being taken with I_1 and the lower with I_2.

We have still to evaluate N, which gives the change in dielectric constant ($\delta\kappa$) due to the release from viscous forces of the dipoles in any temperature-interval $\delta\tau$. There is no easy method of evaluating this with accuracy, although it can be done by very laborious successive approximation, choosing values of N by trial for a series of temperatures until equation (13) fits the observed loss-angle curve. It will be realized, however, that if the release of the dipoles in any one group occurs within a very small temperature-interval, N approximates to $\delta\kappa/\delta\tau$, or as $dr/d\tau \to \infty$, $d\kappa/d\tau \to N$. Fortunately, $dr/d\tau$ for the resin investigated is so great that the dipoles of any one group are completely released within a temperature-interval of 5 to 10 deg. C., and since in any case a numerical integration over 5-degree intervals is involved, there can be no great error in approximating. Thus

$$N \simeq \frac{\delta\kappa}{\delta\tau} \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

Owing to the effect of the term $1/T$ in the Debye equations, which slightly decreases the rise of dielectric constant due to release of dipoles, the value of $\delta\kappa/\delta\tau$ appropriate to (17) is not the value directly measured, but a slightly corrected value given by

$$N \simeq \frac{\delta\kappa}{\delta\tau} + \frac{\kappa}{T} \quad . \quad . \quad . \quad . \quad . \quad (18)$$

For the resin investigated, this equation is quite accurate

for temperatures up to about 50° C. and is still a good approximation at 100° C.

It is now possible to express equation (13) in terms which can all be measured or evaluated, as follows:—

$$\tan \delta_\theta = \frac{1}{\kappa_\theta}\sum_a^\theta NF(\kappa)\Big[I_{01} - I_1\Big]_{\tau-\beta}^{\tau+\beta} + \frac{1}{\kappa^\theta}\sum_\theta^b NF(\kappa)\Big[I_{02} - I_2\Big]_{\tau-\beta}^{\tau+\beta}. \quad (19)$$

where the symbols are defined thus:—

δ_θ = loss angle at temperature θ;
κ_θ, κ_τ = dielectric constant at temperatures θ and τ respectively;
θ = temperature for which $\tan\delta$ is to be calculated;
τ = average temperature of any small temperature-interval 2β, the summation being carried out over all such intervals;
a, b = lower and upper limits of temperature, outside which N becomes negligible;
I is as defined by equations (14), (15), and (16);
$F(\kappa)$ is as defined by equation (12);
and N is as defined by equation (18).

Table 5

τ	κ_τ	$F(\kappa)$	$\delta\kappa/\delta\tau$	$I_{01}-I_1$	$I_{02}-I_2$	$\kappa_\theta \tan\delta$	$\tan\delta$
67·5	4·07	1·98	0·035	0·01		0·001	
72·5	4·28	1·85	0·046	0·04		0·003	
77·5	4·53	1·70	0·061	0·15		0·015	
82·5	4·90	1·53	0·086	0·46		0·061	
87·5	5·40	1·33	0·123	1·21		0·198	
92·5	6·13	1·10	0·157	2·24		0·387	
97·5	6·91	0·91	0·160		2·27	0·333	
102·5	7·66	0·78	0·130		1·41	0·143	
107·5	8·10	0·71	0·072		0·80	0·041	
112·5	8·25	0·69	0·022		0·42	0·006	
117·5	8·25	0·69	—		0·25	—	
					Sum	1·188	0·182

$\theta = 75°$ C. + 20° = 95°; $\kappa\theta = 6·52$; $\tan\delta$ (observed) = 0·202; $\tan\delta$ (calculated) = 0·182.

It should be noted that temperatures are not expressed in degrees above the Centigrade zero, but above an arbitrary starting-point defined by the constant c in equation (6). For the particular resin here investigated, a temperature of τ° C. is a temperature of $(\tau + 20)$ on the arbitrary scale.

Table 5 shows a sample calculation of $\tan\delta$ for one point on the 50-kc./sec. loss curve, at a temperature of 75° C. The data for the column headed $\delta\kappa/\delta\tau$ in this Table were obtained from Fig. 6, which gives the corrected values of $\delta\kappa/\delta\tau$ calculated from the experimental data. To the degree of approximation discussed above in connection with the evaluation of N, these curves give the relative number of dipoles released as a function of temperature. The effect of a more accurate evaluation would be to raise the maxima of the curves somewhat, and to give a rather more rapid fall on the high-temperature side. The values of the integral terms were obtained from Tables 7 and 8 in Appendix II. The value of α was taken as 1 510, from the experimental results of Fig. 3, which refer to measurements of the conductivity obtained shortly after application of voltage. It is known, however, that the value of α would not be significantly different if derived from measurements of the final conductivity, particularly for that part of the conductivity curve (below 100° C.) with which we are here concerned.

Similar calculations to those of Table 5 have been

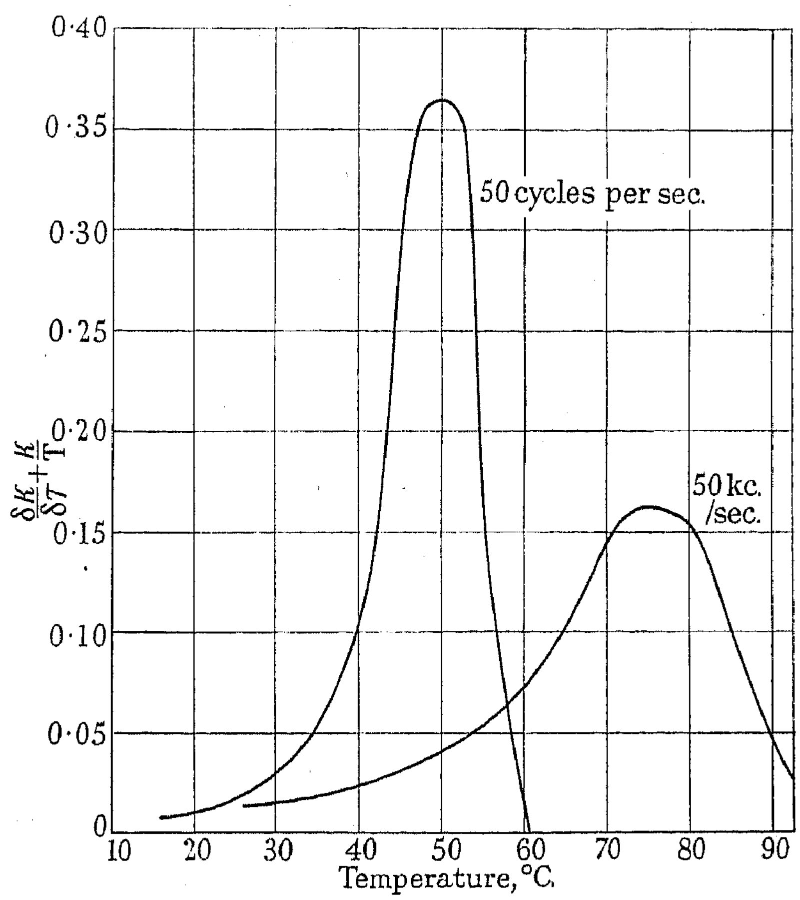


Fig. 6.—Variation of $\delta\kappa/\delta\tau$ (corrected) with temperature at 50 cycles per sec. and at 50 kc./sec.

carried out for all points on the 50-cycle and 50-kc./sec. loss-angle curves at intervals of 5 degrees. The results are shown in Fig. 7, where the curves represent the observed values and the points the calculated values. Considering the numerous simplifying assumptions and approximations involved, it is thought that the agreement is fairly satisfactory. The present hypothesis demonstrates the consistency between the d.c. conductivity, the dielectric constant, and the power factor, regarded as functions of temperature and frequency (although only two frequencies were actually tested), without the intervention of any constants or values of a "disposable" nature. The only fundamental assumptions are, firstly, that the effects are all due to a heterogeneous collection of dipoles, whereas the equations would also be consistent with a mechanism of the Wagner type. However, the material is pure and is known to be of

dipolar structure. Other sources of loss exist—either in the pure or in deliberately contaminated material—but have no effect over the range considered, so that there is no *a priori* reason for envisaging any other than the dipolar mechanism. Secondly, the ionic and dipolar viscosities are presumed the same; this is the simplest hypothesis and one which seems to be justified by the facts.

The present treatment is thus more rigid than the related work of W. A. Yager already mentioned,[18] which refers the phenomena to a Wagner mechanism. The comparison given in Table 6 indicates the greater number of "disposable" parameters in Yager's theory. Thus Yager employs non-observed values of κ_0 and κ_∞ and, more important, uses data from the loss-angle curve to calculate this curve theoretically.

As regards the residual discrepancies between the observed and calculated values of Fig. 7 (see page 627), it is known that better agreement on the high-temperature side of the curves could be obtained by a more accurate evaluation of N, but the work involved is extremely laborious. The discrepancy on the low-temperature side appears to be more fundamental, and although much time has been devoted to a search for the cause no better agreement can be obtained. It has been ascertained that the error is not due to either:—

Table 6

Yager	Present method
κ_0 calculated indirectly κ_∞ calculated indirectly	Observed values of κ
Observed slope of κ	Observed slope of κ
Observed slope of tan δ	Observed slope of d.c. resistivity curve

(A) The slow rise of κ at low temperatures, which appears to be independent of the main Debye region and to be associated with the small secondary maximum. The slope of this increase is far too small to account for the discrepancy.

Or (B) a failure of the assumed relationship between molecular viscosity and the d.c. conductivity. A modification of this relationship sufficient to correct the results at 50 kc./sec. would completely destroy the agreement at 50 cycles per sec. It may be noted that equation (7) for the molecular viscosity appears to hold with remarkable accuracy. The highest observed value of R is $10^{13 \cdot 28}$ at 61·7° C., yet this was extrapolated to $10^{16 \cdot 2}$ at 40° C. in calculating the 50-cycle losses, and the agreement is still good.

It seems likely that the discrepancy arises from an incorrect derivation of $F(\kappa)$, which expresses the effect upon the dipoles of the changing characteristics of the medium. A number of reasonable alternatives for this function has been investigated but none as yet found gives better results than equation (12).

The foregoing treatment applies, of course, only to the region of the main Debye maximum in the loss angle. The rise of tan δ at higher temperatures is adequately accounted for by conduction losses. The secondary maximum at low temperatures remains unexplained, and it would be very desirable to attempt measurement of the resistivity in this region with a view to applying the methods of this paper to the prediction of the secondary maximum, and also to determine the temperature at which equation (6) ceases to hold.

(5) CONCLUSIONS

The following are the main conclusions which can be drawn from this work.

(*a*) The polarity of amorphous solids is a property of the material and is not appreciably dependent upon small quantities of polar impurities.

(*b*) The direct-current conductivity of a pure resin is dependent, but not very critically dependent, upon small quantities of polar impurities.

(*c*) The "static" dielectric constant of amorphous polar solids varies with temperature in a similar way to the dielectric constant for alternating current, when measured with a time of discharge of the order of 1 sec.

(*d*) The direct-current conductivity of a pure resin obeys closely an inverse exponential law of temperature, provided that this be measured from an arbitrary zero point.

(*e*) The practical advantages of a pure resin as compared with one containing 2 % or 3 % of impurity are negligible, unless the lowest possible conductivity is required.

(*f*) At temperatures where both the polar and the conductivity losses are small, the loss due to any third cause is very small (tan $\delta < 0 \cdot 003$) and probably zero.

(*g*) The pure resin has characteristics which are only qualitatively explained by the simple Debye theory.

(*h*) It is not possible to find any modification of Debye's theory which will account for the observed results without the hypothesis of a distribution of relaxation times.

(*j*) If such a distribution be assumed, the losses can be predicted quantitatively from the observed values of κ and R.

(*k*) The variation of molecular viscosity with temperature proves to be the same as the variation of d.c. resistivity.

(6) ACKNOWLEDGMENTS

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(7) REFERENCES

Complete bibliographies will be found in References (13), (14), and (15) below. The other References are to some of the more important papers which have made additions to the theory of the subject, or which are referred to in the text.

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APPENDIX I

The Preparation of Chemically Pure Glycol Phthalate

Glycol phthalate is an equi-molecular condensation product of ethylene glycol and phthalic anhydride. General information as to its preparation and properties will be found in Reference (1).

It was desired to prepare a specimen for electrical tests which should be free not only from impurities introduced with the constituent substances, but also from oxidation products formed during the reaction and from any uncombined residue of the constituents. The special technique necessary to achieve this is briefly described in this Appendix. The ethylene glycol used was material of "puriss." grade, and was not further purified.

The best phthalic anhydride obtainable contained, apart from phthalic acid, some unidentified impurity which rapidly oxidized above 150° C., giving a black tarry residue, and which proved extremely difficult to eliminate. The original impure material turned black immediately when boiled in a test tube in air (boiling point 285° C.). It was accepted as sufficiently pure when it darkened only very slightly after 10 minutes of this treatment.

Several of the conventional methods of purification were tried, but none would give a product meeting the above test. Finally, sublimation *in vacuo* was found to be satisfactory. An apparatus developed for this purpose, of molybdenum glass, to give strength and avoid contamination of the product, comprised a spherical bulb of about 10 cm. diameter fitted by a ground joint to a wide tube about 35 cm. long and 5 cm. diameter. The upper end of this communicated with the vacuum pump. The bulb is immersed in an oil bath, and the joint must be maintained at a sufficient temperature to prevent the product from condensing over it and preventing the apparatus from being opened.

At pressures less than about 2 mm. Hg, phthalic anhydride has no liquid phase, and a sample placed in the bulb of the above apparatus will sublime directly into the tube above it at a temperature of about 130° C. It deposits in a very solid mass, which is difficult to withdraw from the tube. The withdrawal must be done mechanically, not by heating the tube, or the latter is broken by expansion of the material. The apparatus might be improved in this respect. The temperature must be carefully controlled, as too high a rate of sublimation decreases the purity of the product and may block the tube completely. A sublimation rate of about 50 g. per hour was found suitable for the size of apparatus given.

With this apparatus, 300 g. of phthalic anhydride were sublimed six times—twice at 100° C., at which temperature the material did not pass over in any quantity, to remove volatile impurities; and four times at 135° C., in which case the material sublimed and non-volatile impurities remained. After the sixth run, the entire material sublimed without visible residue, and the product began to darken only after 15 minutes' boiling in air.

Several small samples of resin, about 2 g. each, were made to find the best conditions for the reaction. All samples darkened during the condensation reaction when this was carried out in air, and gave a resin showing a yellow colour in thicknesses of 2 mm. It became evident that oxygen must be excluded, and all further work was done in an atmosphere of nitrogen purified by passage over hot copper gauze. Samples prepared in nitrogen gave an almost colourless product when the reaction proceeded at 205° C., but were strongly coloured at 250° C. From American data[1] it is known that the time required for the reaction to go to 99 % completion at 250° C. is 2 hours, and at 205° C. is 42 hours. Similar samples were made in nitrogen under these two conditions of temperature. The 250° C. sample was much more strongly coloured, although its time of heating was 21 times shorter. Evidently the reaction should be carried out over a long period at the lowest possible temperature. To show that the coloration was not due to impurity in the nitrogen, a sample was heated in a sealed evacuated tube. After 2 hours at 250° C. it had coloured considerably, and after 18 hours at 220° C. it had become a bright red.

Apparently there are two causes of coloration. One is an oxidation, and can be eliminated by heating in nitro-

gen; the other is independent of any external impurity, but occurs when the temperature is raised above about 205° C. Whether this second cause is an inherent property of the resin, or depends upon traces of some remaining impurity, is unknown.

To produce a quantity of the resin, the special flask shown in Fig. 8 was developed. Made of molybdenum glass, it comprises a spherical bulb with a ground stopper carrying a tube through which pure nitrogen can be supplied. The nitrogen escapes through one or other of the holes A and B. During the condensation reaction, when water is being evolved, hole B is sealed and A opened, so that the water vapour is swept out of the flask through the side tube shown. After the completion of the reaction, hole A is sealed and B opened, so that the

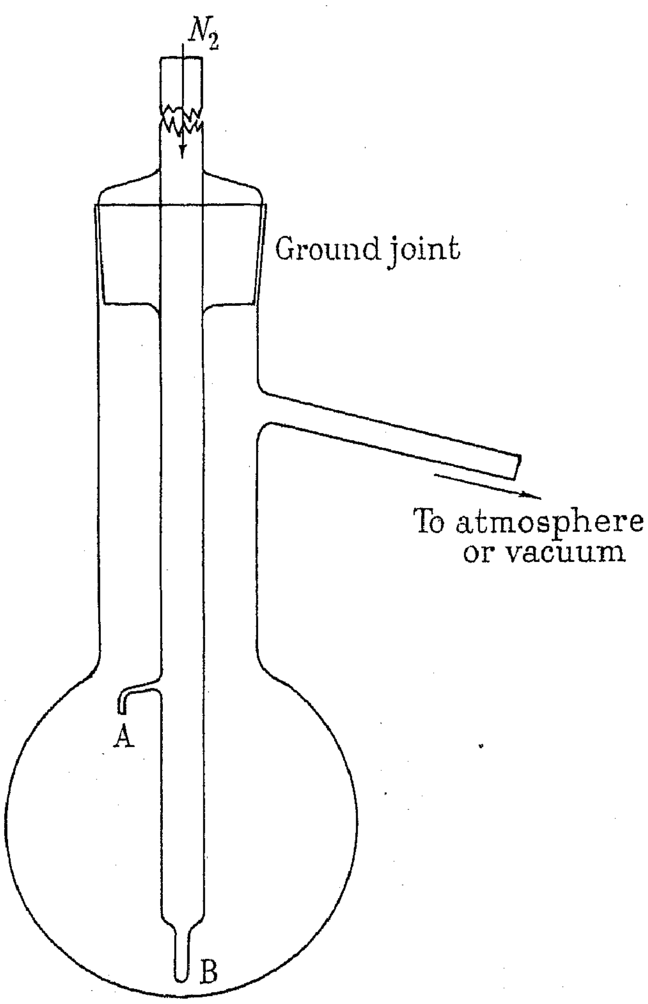

Fig. 8.—Apparatus for preparation of resin.

nitrogen bubbles through the resin and removes uncombined traces of the reagents. A thermometer may be placed within the tube if desired.

In this apparatus, 204 g. of re-sublimed phthalic anhydride and 86 g. of ethylene glycol were heated at 205° C. in a stream of nitrogen at atmospheric pressure for 24 hours, after which time there appeared to be negligible formation of water. The nitrogen flow was then altered so that gas would bubble through the resin at a pressure of 1 mm. Hg. This was continued for 20 hours, during the first part of which time free phthalic anhydride and glycol distilled from the resin and deposited in the upper cool part of the flask. This mixture was removed from time to time, and in all 20 g. were collected. During the last 5 hours of purification, no visible material was released from the resin. A small cylinder of filter paper in the neck of the flask, during the last few hours, helps in the collection of any liquid which may be liberated.

An attempt was made to measure the conductivity of the resin during purification. The results were not accurate, owing to the difficulty of introducing electrodes into the flask, but they showed an improvement of about 5 : 1 during the 20 hours' purification.

The resin obtained was a brittle, glass-like substance, which began to soften at about 60° C. and was liquid at 100° C. At 200° C. it was a watery, colourless liquid which did not darken in air during 3 hours at this temperature. It did not liberate any visible vapour, but had a slight odour at 200° C. In the solid form, it appeared perfectly colourless in a thickness of 0·5 cm., but was faintly yellow in a thickness of 2 cm. Its acid number was measured as 1·5.

APPENDIX II

The Computation of a Certain Integral

In connection with equation (13) it is necessary to compute the expression

$$I = \int_a^b \frac{e^{\frac{\alpha}{\theta}} e^{-\frac{\alpha}{\tau}}}{e^{\frac{2\alpha}{\theta}} e^{-\frac{2\alpha}{\tau}} + 1} d\tau \quad \text{where} \quad a < \theta < b$$

The solution can be expressed in convergent form only when the integration is performed between certain limits such that

$$I = (I_{01} - I_1) + (I_{02} - I_2)$$

where the suffixes indicate integration between the following pairs of limits, respectively: $(\theta, 0)$ $(a, 0)$ $(-\eta, \theta)$ $(-\eta, b)$, η being an indefinitely small quantity. The validity of the integration through zero of the two final terms has not been investigated in detail and is thought to be invalid; but for the purposes of the present investigation this is immaterial, as any residual due to this process will cancel out in the difference between the two terms.

We proceed to integrate the second term, which may be written

$$I_1 = \int_0^\tau \frac{e^{\frac{\alpha}{\theta} - \frac{\alpha}{\tau}}}{e^{2\left(\frac{\alpha}{\theta} - \frac{\alpha}{\tau}\right)} + 1} d\tau \text{ for } \tau \leqslant \theta$$

Writing $\alpha/\tau = x$, $\alpha/\theta = y$, and performing the division, this becomes

$$I_1 = -\alpha \int_x^\infty \frac{dx}{x^2} \sum_{n=1}^\infty (-1)^n e^{my} e^{-mx}$$

where $m = 2n - 1$. Rearranging,

$$\begin{aligned} I_1 &= -\alpha \sum_{n=1}^\infty (-1)^n e^{my} \int_x^\infty \frac{e^{-mx}}{x^2} dx \\ &= \alpha \sum_{n=1}^\infty (-1)^n e^{my} \left\{ \left[\frac{e^{-mx}}{x} \right]_x^\infty + m \int_x^\infty \frac{e^{-mx}}{x} dx \right\} \\ &= -\alpha \sum_{n=1}^\infty (-1)^n e^{my} \left\{ \frac{e^{-mx}}{x} + mEi[-mx] \right\} \end{aligned}$$

Table 7

VALUES OF $\frac{100 I_1}{\tau} = 100 \sum_{n=1}^{\infty} (-1)^n e^{m(y-x)} \sum_{s=1}^{\infty} (-1)^s \frac{s!}{(mx)^s}$

$x \rightarrow$ / $y \downarrow$	12·58	13·12	13·72	14·38	15·10	15·90	16·78	17·78	18·88	20·15	21·60	23·25
12·58	5·290	3·460	1·980	1·008	0·470	0·202	0·080	0·029	0·008	0·002		
13·12		5·090	3·193	1·715	0·818	0·350	0·138	0·049	0·015	0·004		
13·72			4·910	2·930	1·450	0·642	0·253	0·089	0·028	0·007	0·002	
14·38				4·729	2·660	1·209	0·482	0·172	0·053	0·014	0·003	
15·10					4·520	2·370	0·980	0·354	0·110	0·029	0·006	0·001
15·90						4·332	2·085	0·770	0·244	0·065	0·014	0·002

$x \rightarrow$ / $y \downarrow$	16·78	17·78	18·88	20·15	21·60	23·25	25·20	27·45	30·20	33·55	37·75	
16·78	4·120	1·800	0·590	0·158	0·030	0·006	0·001					
17·78		3·967	1·526	0·423	0·094	0·017	0·002					
18·88			3·716	1·254	0·286	0·050	0·006	0·001				
20·15				3·505	0·989	0·179	0·024	0·002				
21·60					3·306	0·750	0·105	0·009	0·001			
23·25						3·099	0·526	0·049	0·006			
25·20							2·860	0·345	0·020	0·001		
27·45								2·641	0·198	0·006		
30·20									2·418	0·098	0·001	
33·55										2·190	0·038	
37·75											1·962	0·010

The first entry in each line gives the value of $100 I_{01}/\tau$.

in which $Ei[-mx]$ is the negative exponential integral, for which tables exist. But when $mx \gg 1$, as it is in the present application of the integral,

$$Ei[-mx] \simeq -\frac{e^{-mx}}{mx}\left\{1 + \sum_{s=1}^{\infty} (-1)^s \frac{s!}{(mx)^s}\right\} \quad \text{for } mx \gg 1$$

Therefore, referring to equation (14),

$$I_1 \simeq \tau \sum_{n=1}^{\infty} (-1)^n e^{m(y-x)} \sum_{s=1}^{\infty} (-1)^s \frac{s!}{(mx)^s} \quad \text{for } mx \gg 1$$

For the special case when $\tau = \theta$ this reduces to

$$I_{01} \simeq \tau \sum_{n=1}^{\infty} (-1)^n \sum_{s=1}^{\infty} (-1)^s \frac{s!}{(mx)^s}$$

which [see equation (16)] reduces to

$$I_{01} = \tau\left(\frac{\pi}{4x} - \frac{1 \cdot 834}{x^2} + \frac{5 \cdot 8}{x^3} - \frac{23 \cdot 7}{x^4} \cdots \frac{s!}{x^s}\right)$$

The integration of I_2 and I_{02} follows similar lines, except that the positive exponential integral is involved, causing the changes of sign shown in equation (15) as compared with equation (14). The absolute values given by equation (15) may be in error owing to the limits chosen, as already remarked, but the final result is correct, and has been checked by numerical integration.

Fortunately, the series involved are rapidly convergent, and equations (14), (15), and (16) have been computed to slide-rule accuracy over the range required for the present work. Tables 7 and 8 give the resulting values. The odd values of the argument which have been selected are due to the use, for convenience in the present work, of exact values of temperature instead of exact values of the variables x and y. The tabulated values are, however, quite general, and do not involve any experimental constants.

APPENDIX III

A Simple Medium-Frequency Bridge

The bridge used to obtain the 50-kc./sec. values of dielectric constant and loss angle in this work was specially developed to meet a shortage of precision apparatus. Since it requires few and simple components, and yet gave accurate results with reasonable convenience, it seems worth while to record the circuit used. This is shown in Fig. 9. The oscillatory circuit LC, together with the capacitances in the bridge, form part of a 50-kc./sec. push-pull oscillator. The two halves of the inductance are closely coupled, and the centre point brought out to earth. The bridge proper consists of two similar condensers C_1 and C_2, which need not be loss-free provided that they are similar; a variable loss-free condenser C_3 of capacitance at least equal to the sample; and the capacitance C_x formed by the sample itself. The resistances R_1 and R_2 are necessary for phase-angle correction. The detector circuit consists of a sensitive valve voltmeter. Provided that the condensers C_1 and

Table 8

VALUES OF $\dfrac{100 I_2}{\tau} = -100 \sum_{n=1}^{\infty} (-1)^n e^{m(x-y)} \sum_{s=1}^{\infty} \dfrac{s!}{(mx)^s}$

$y \downarrow$ \ $x \rightarrow$	37·75	33·55	30·20	27·45	25·20	23·25	21·60	20·15	18·88	17·78	16·78	15·90
37·75	2·220	0·048	0·002									
33·55		2·519	0·123	0·009								
30·20			2·824	0·250	0·028	0·009						
27·45				3·135	0·436	0·068	0·014	0·004				
25·20					3·451	0·672	0·140	0·035	0·011	0·004		
23·25						3·773	0·966	0·249	0·076	0·026	0·011	0·004

$y \downarrow$ \ $x \rightarrow$	21·60	20·15	18·88	17·78	16·78	15·90	15·10	14·38	13·72	13·12	12·58	11·60
21·60	4·088	1·300	0·401	0·141	0·056	0·024	0·012	0·006	0·003			
20·15		4·433	1·651	0·593	0·238	0·105	0·050	0·025	0·014	0·007	0·005	
18·88			4·774	2·050	0·830	0·368	0·176	0·091	0·050	0·028	0·017	
17·78				5·106	2·430	1·113	0·537	0·278	0·153	0·088	0·055	
16·78					5·480	2·859	1·424	0·740	0·411	0·237	0·145	
15·90						5·857	3·290	1·795	0·986	0·580	0·348	
15·10							6·220	3·736	2·156	1·271	0·774	
14·38								6·614	4·200	2·565	1·582	
13·72									6·976	4·669	2·995	
13·12										7·370	5·120	
12·58											7·775	3·900

The first entry in each line gives the value of $100 I_{02}/\tau$.

C_2 are similar, the only component of the bridge which need be free from residual errors is the condenser C_3. Residual errors in any of the other components will result only in second-order corrections which are quite negligible for any but the most accurate measurements.

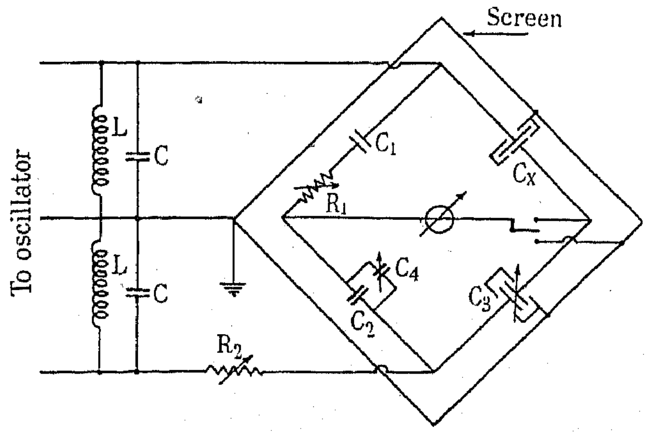

Fig. 9.—Bridge circuit.

Error due to the capacitance to earth from the junction of R_1 with C_1 may be minimized by using a value of C_1 not less than $0 \cdot 001\ \mu$F, or, if the capacitance to earth be approximately known, a correction may be applied. The bridge has not been used above 50 kc./sec. but it is thought that by careful design it might be used up to possibly 500 kc./sec.

The bridge may be regarded as a modified form of the Fleming–Dyke four-condenser bridge,[21] improved by screening and the use of a double balance. The method of balancing is as follows: With the detector connected to the screen, balance is obtained on C_4 and R_2. C_4 may be placed in whichever side of the bridge is necessary to correct for any small lack of balance in the two halves of the oscillatory circuit. Its value should always be very small. The detector is then thrown over to the bridge, and balance obtained on C_3 and R_1. This will have disturbed the first balance somewhat, and balance is obtained again on the screen and on the bridge alternately until both are simultaneously balanced, in the well-known way. When this is attained,

$$C_x = \frac{C_3}{1 + \tan^2 \delta} \, \frac{C_1}{C_2 + C_4}$$

$$\tan \delta = \omega C_1 R_1$$

Although quite makeshift components were used, it was possible to measure a capacitance of $100\ \mu\mu$F to $\pm 0 \cdot 2\ \mu\mu$F and the phase angle to $\pm 0 \cdot 0002$. The loss angle of air condensers was correctly indicated as zero. A disadvantage of the bridge is that the frequency varies slightly with the capacitance of the sample, but this effect is small if the oscillatory circuit be designed with a large value of capacitance, and in any case can be compensated if desired.

AN OSCILLOGRAPHIC TECHNIQUE FOR MEASUREMENTS IN A NETWORK ANALYSER*

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SUMMARY

Two new methods of measurement in alternating-current networks are described. Each method involves the use of a cathode-ray oscillograph, together with a precision-type phase-shifting transformer, a calibrated potential divider, and amplifying equipment. One, a null method, is capable of very high accuracy. The other, although not capable of the same degree of accuracy, has certain definite advantages. It is particularly useful, for instance, in the analysis of networks containing elements with variable parameters, and in the investigation of transient phenomena in networks.

The manner of operation of the measuring equipment is illustrated by a series of photographic records.

(1) INTRODUCTION

The calculations involved in the design and operation of modern electrical distribution systems frequently present such intricate equations that their solution by analytical means is impracticable. Many calculations of this nature may be avoided by the use of a network analyser, in which the distribution system is set up in miniature and the required knowledge obtained by actual measurements on the miniature network. These measurements can be interpreted for the system itself by electrical similarity. (The term network analyser is usually applied to an installation consisting of the miniature network, together with the measuring equipment.) Various forms of network analyser have been described elsewhere.‡

The miniature system consists of a number of generators, resistors, reactors, and other circuit components. In an alternating-current network it is not necessary to use the frequency of the system itself, and in many cases it is desirable to adopt a higher frequency. The frequency chosen has a considerable influence on the design of the measuring equipment, and particular attention has been given in the past to this question.

The measuring equipment must be capable of determining both the magnitude and the phase of any relevant voltage or current in the network. The equipment is therefore usually designed to measure voltage, current, and power; for convenience in operation it is desirable to measure all three simultaneously. The essential requirements of the measuring equipment are (*a*) that its application to a particular measurement should not affect the conditions in the network, (*b*) that it must be suitable for the frequency at which the analyser operates, and (*c*) that it should cover the complete range of values of voltage and current likely to occur in the network.

The first of these requirements may be satisfied by the use of "buffer amplifiers," as in the analyser described by Kuehni and Lorraine,‡ or by other means. The second presents no special difficulties if the analyser operates at a normal commercial frequency, such as 50 or 60 cycles per sec., but there are difficulties associated with higher frequencies. The third requirement is easily satisfied.

This paper describes a new technique for taking measurements in a miniature network. It is equally applicable to any frequency of supply which may be conveniently generated, and has a negligible effect on the electrical conditions in the network. All measurements are made by comparison: no absolute measurements are required, and difficulties associated with the usual measuring instruments, at frequencies higher than normal, are not encountered.

Two distinct methods of measurement are described, each of which involves the use of a cathode-ray oscillograph. One method is very convenient in that it provides a visual indication of the quantity to be measured. The other is a null method, capable of a high degree of precision.

The former method may also be used for the examination of transient phenomena occurring in the network.

Although the cathode-ray oscillograph is used as an indicating instrument, no actual measurements need be taken on the screen of the oscillograph.

The oscillographic technique possesses an additional advantage in being able to withstand severe overload conditions without damage to the apparatus.

(2) METHODS OF MEASUREMENT

In order to obtain all required information from a miniature network, it is necessary to determine any relevant voltage or current in both magnitude and phase. The current in any arm of the network may be determined in terms of the potential difference across a pure resistance in that arm, so that it is sufficient to provide a technique for determining a voltage in both magnitude and phase. In the methods described in this paper the measurements of voltage are made, not absolutely, but by comparison with a "standard" voltage, to which are ascribed unit amplitude and zero phase. Normally, the terminal voltage of one of the generators in the miniature network is taken as the standard.

The comparison is made by means of an "intermediate" voltage which is derived from the standard voltage through a phase-shifting transformer and a potential divider. The transformer and potential divider are calibrated in such a way that the inter-

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† Australian National Standards Laboratory.

‡ See References.

‡ See Reference (4).

mediate voltage is determined from their readings, in terms of the standard voltage. In order to measure an unknown voltage in the miniature network, the intermediate voltage is varied until it is identical with the unknown voltage. The latter is then determined by the readings of the phase-shifting transformer and the potential divider. The above process is illustrated in Fig. 1.

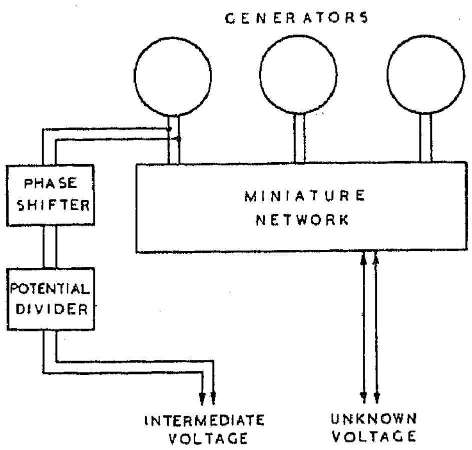

Fig. 1.—Diagram showing the manner of obtaining the intermediate voltage which is to be compared with the unknown voltage.

The two available methods differ in the manner in which the equality of the intermediate and unknown voltages is indicated. They will be referred to as "the coincidence method" and "the null method."

The Coincidence Method

In the first method, both the intermediate and the unknown voltages are indicated simultaneously on the screen of a cathode-ray oscillograph, in reference to a suitable time-base. For this purpose it is necessary to use a two-way switching device, and a form of electronic relay switch, developed by one of the authors,* is most suitable. The electronic relay switch is an electronic device which fulfils the purpose of a two-pole two-way switch. By its use, voltages proportional to the intermediate and the unknown voltages are applied alternately to the oscillograph, and curves representing both are visible simultaneously on the screen.

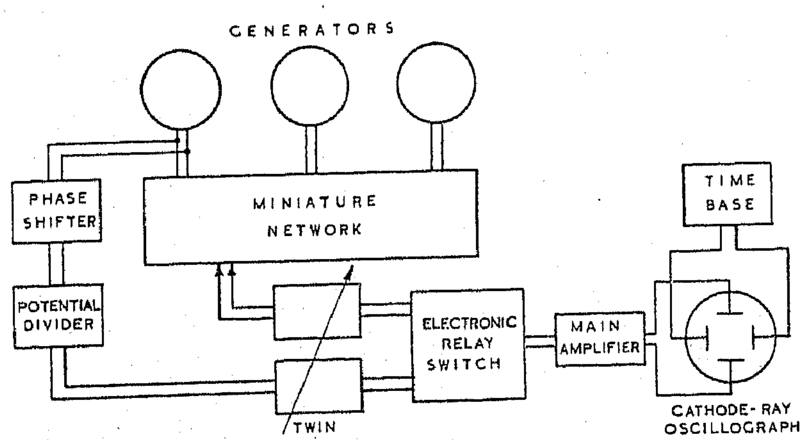

Fig. 2.—Measurement of the unknown voltage by the coincidence method.

The phase-shifter and the potential divider are adjusted manually so that the two curves come into coincidence. When this condition is reached, the unknown and intermediate voltages are identical, and so the scale readings of the potential divider and the phase-shifter give the amplitude and phase of the unknown voltage. A line diagram of the circuit is shown in Fig. 2.

The unknown voltage may vary in magnitude over a very wide range. The twin amplifiers preceding the electronic relay switch enable the two input voltages to it to be brought to a suitable value for its proper operation. They are exactly similar in design and have the same amplification ratio, this being adjusted by a single control switch.

The accuracy of this method depends on the precision with which the coincidence of the curves may be detected. If the wave-form of either, or both, of the voltages has a slight harmonic content, the accuracy obtainable by this method may be insufficient.

In order to obtain greater accuracy, the coincidence method is replaced by a null method of indication, which is more satisfactory, in general, for measurements applying to a steady-state condition. The coincidence method has been retained, however, partly because of the visual indication which it provides, and partly because the apparatus may be used in transient analysis.

The Null Method

As in the previous method, the measurement is made by the comparison of the unknown with the intermediate voltage. In the null method, the difference of the two voltages is applied after amplification to the cathode-ray oscillograph. If they are both sinusoidal, the difference is also sinusoidal and the measurement is effected by adjusting the phase-shifting transformer and the potential divider until the amplitude of the curve on the screen of the oscillograph falls to zero.

There is no limit, theoretically, to the amplification which may be used as balance is approached, and therefore to the sensitivity of the method. In practice, however, the voltages will not be exactly sinusoidal, and, in general, harmonics will appear, even when the fundamental voltages have been balanced. This fact sets an upper limit on the amplification used. The limit may be increased by the introduction of a tuned circuit into the amplifier, so that voltages at a frequency higher than the fundamental are considerably attenuated. An additional

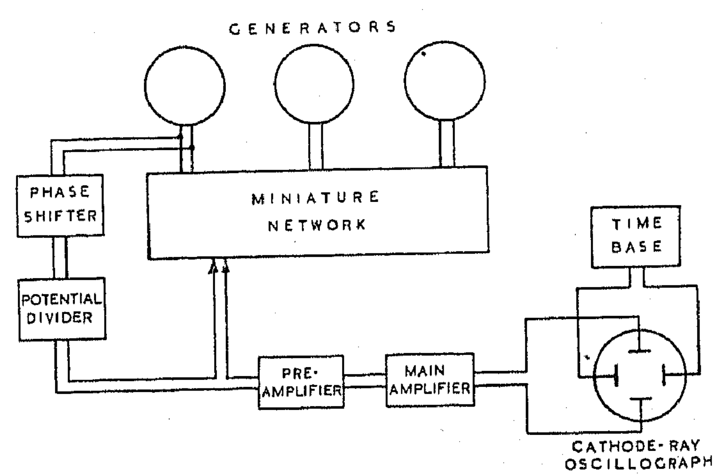

Fig. 3.—Measurement of the unknown voltage by the null method.

* W. K. Clothier: *Journal of Scientific Instruments*, 1939, vol. 16, p. 285.

advantage of the tuned amplifier is that the curve on the screen of the oscillograph is thereby smoothed out, enabling the observer more easily to detect the condition of balance.

A line diagram of the circuit is shown in Fig. 3. A change from the coincidence method to the null method, or vice versa, is effected by the use of a single switch.

(3) THE MINIATURE NETWORK

It is considered irrelevant to give a detailed description of the miniature network, as it includes no substantial departures from established practice. It is sufficient to state that the network is supplied by sine-wave alternators generating 50 volts (r.m.s.) at 150 cycles per sec., and their e.m.f.'s under full-load conditions have a total harmonic content of less than 1 %. It was decided that the lowest voltage likely to require measurement would not be less than 0·05 volt, thus giving a ratio of 1 000 to 1 between the upper and lower limits of voltage to be measured. The design of the measuring equipment is affected to a large extent by the figures quoted above.

(4) DETAILED CIRCUIT DESCRIPTION

The Measuring Components

In both the coincidence and the null methods of measurement a calibrated phase-shifter and a calibrated

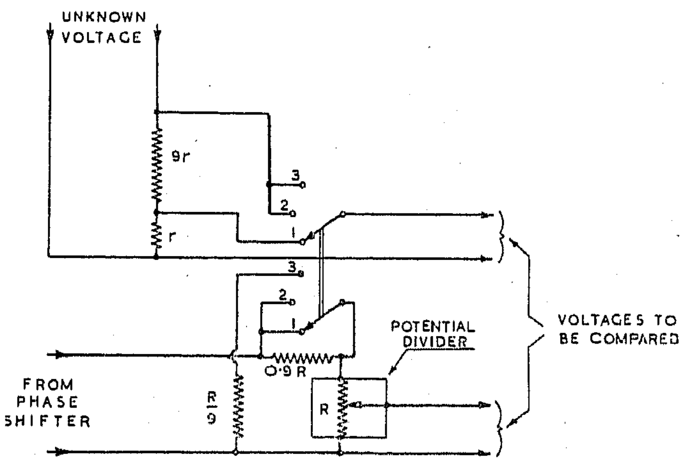

Fig. 4.—Range switching circuit.

potential divider are used for obtaining the intermediate voltage. A short description of these components follows.

The phase-shifting transformer.

This is a mechanical phase-shifter with a bi-phase stator supplied from a phase-splitting circuit. The output is taken from the rotor winding and its phase is varied, without change in magnitude, by angular rotation of the rotor. The phase angle of the output is indicated by a calibrated scale mounted on the rotor shaft.

The calibrated potential divider.

The potential divider, which has low resistance, is of wire-wound construction, the resistance element being tapered in such a way that the scale is reasonably open over its working range. It is used in conjunction with a range switch and a number of fixed resistances, as shown by the circuit diagram of Fig. 4. With the switch in position 1, the unknown voltage is reduced in the ratio 1:10, whilst in position 3 the intermediate voltage is similarly reduced. With the switch in position 2, the two voltages are unchanged. These arrangements allow a sufficient order of accuracy to be obtained when measuring any voltage within the wide range required.

The Coincidence Method of Measurement

The principle of this method of measurement has already been described. A detailed circuit diagram appears in Fig. 5, where Figs. 5(*a*), 5(*b*), and 5(*c*), show respectively the twin amplifiers, the electronic relay switch, and the main amplifier. The output of the main amplifier is supplied to the vertically deflecting plates of the cathode-ray oscillograph. These various elements will be described in turn.

The twin amplifiers (Fig. 5a).

It has already been stated that the function of the twin amplifiers is to adjust the magnitudes of the unknown and intermediate voltages to values suitable for application to the electronic relay switch. The amplifications are identical, and can be controlled in steps in such a way that the amplification is doubled for each succeeding position of a rotary gain-control switch. The ganged switches S1, S2, and wire-wound resistances P1, P2, perform this function. The amplifications of the two amplifiers are made equal by adjustment of a rheostat R9 which is provided in order to allow compensation for slight differences in the valves or other circuit components. The ratio of maximum to minimum amplification covered is $2^7 : 1$, i.e. 128 : 1. The maximum input voltage to either twin amplifier is 5 volts and the minimum 0·05 volt, and for any voltage within this range the twin amplifiers can be adjusted to deliver a suitable magnitude of voltage to the electronic relay switch. This should preferably be between 3 and 8 volts (r.m.s.).

The electronic relay switch (Fig. 5b).

A complete description of the electronic relay switch does not come within the scope of this paper. It is sufficient to state that the electronic relay switch is an electronic device which delivers as its output a composite voltage embodying the relative magnitudes, the waveforms, and the phase relations, of the two input voltages. Its action is the electrical analogy of a mechanical switch connecting the main amplifier alternately to the two input circuits, the output of the main amplifier being supplied to the vertically deflecting plates of the cathode-ray oscillograph. The frequency of switching may be controlled over a wide range. When the switching frequency is considerably greater than that of the input voltages, each voltage wave appears on the oscillograph screen as a series of discrete dots. For a switching frequency equal to half that of the input voltage, complete cycles of the two voltage waves are successively traced on the screen. With the time-base frequency equal to the input-voltage frequency the two waves overlap and have the appearance of unbroken curves. Examples of these two cases appear among the photographic records of Fig. 6.

The range switch S3, S4, and variable rheostat R44, together allow a switching-frequency range from 15 to 13 000 cycles per sec. to be covered.

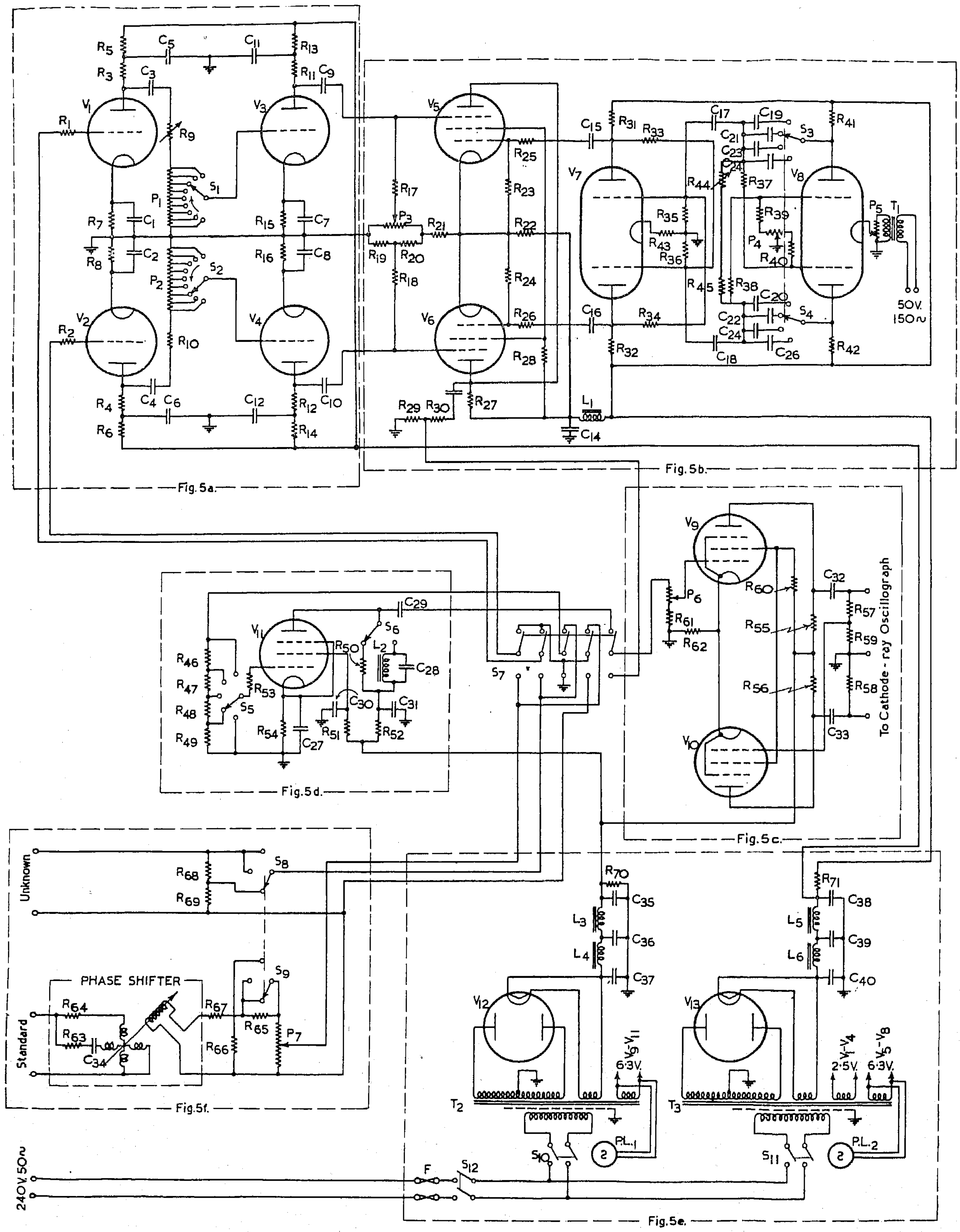

Fig. 5.—Complete wiring diagram. (For data relating to circuit components, see page 643.)

Fig. 5: Data relating to circuit components.

Resistors.

R_1, R_2.	25 000-ohm resistor.
R_3, R_4.	50 000-ohm resistor.
R_5, R_6.	100 000-ohm resistor.
R_7, R_8.	4 500-ohm resistor.
R_9.	20 000-ohm variable resistor.
R_{10}.	10 000-ohm resistor.
R_{11}, R_{12}.	250 000-ohm resistor.
R_{13}, R_{14}.	500 000-ohm resistor.
R_{15}, R_{16}.	20 000-ohm resistor.
R_{17}, R_{18}.	1-megohm resistor.
R_{19}, R_{20}.	500-ohm resistor.
R_{21}.	1 200-ohm resistor.
R_{22}.	25 000-ohm resistor.
R_{23}, R_{24}.	1-megohm resistor.
R_{25}, R_{26}.	1-megohm resistor.
R_{27}, R_{28}.	50 000-ohm resistor.
R_{29}.	100 000-ohm resistor.
R_{30}.	1-megohm resistor.
R_{31}, R_{32}.	25 000-ohm resistor.
R_{33}, R_{34}.	15 000-ohm resistor.
R_{35}, R_{36}.	10 000-ohm resistor.
R_{37}, R_{38}.	100 000-ohm resistor.
R_{39}, R_{40}.	25 000-ohm resistor.
R_{41}, R_{42}.	10 000-ohm resistor.
R_{43}.	25 000-ohm resistor.
R_{44}.	1-megohm variable resistor.
R_{45}.	25 000-ohm resistor.
R_{46}.	100 000-ohm resistor.
R_{47}.	20 000-ohm resistor.
R_{48}.	4 000-ohm resistor.
R_{49}.	1 000-ohm resistor.
R_{50}.	100 000-ohm resistor.
R_{51}.	1·15-megohm resistor.
R_{52}.	175 000-ohm resistor.
R_{53}.	25 000-ohm resistor.
R_{54}.	2 000-ohm resistor.
R_{55}, R_{56}.	30 000-ohm resistor.
R_{57}, R_{58}.	1-megohm resistor.
R_{59}.	30 000-ohm resistor.
R_{60}.	125 000-ohm resistor.
R_{61}.	25 000-ohm resistor.
R_{62}.	850-ohm resistor.
R_{63}. R_{64}.	These resistors are adjusted so that the currents in them are equal in magnitude, and are in phase quadrature.
R_{65}.	Resistor, of value (in ohms) given by $0 \cdot 9 \times P_7$.
R_{66}.	Resistor, of value (in ohms) given by $\frac{1}{9} \times P_7$.
R_{67}.	This resistance is adjusted to give a suitable current in P_7.
R_{68}.	90 000-ohm wire-wound resistor.
R_{69}.	10 000-ohm wire-wound resistor.
R_{70}.	25 000-ohm wire-wound resistor.
R_{71}.	7 000-ohm wire-wound resistor.

Potentiometers.

P_1, P_2.	Wire-wound potential divider with 8 sections, of 1 000, 1 000, 2 000, 4 000, 8 000, 16 000, 32 000, 64 000 ohms.
P_3.	1 000-ohm potentiometer.
P_4.	25 000-ohm potentiometer.
P_5.	30-ohm potentiometer.
P_6.	1-megohm potentiometer.
P_7.	270-ohm calibrated potential divider.

Condensers.

C_1, C_2.	25-μF electrolytic condenser.
C_3, C_4.	0·25-μF condenser.
C_5, C_6.	4-μF condenser.
C_7, C_8.	25-μF electrolytic condenser.
C_9, C_{10}.	0·1-μF condenser.
C_{11}, C_{12}.	1 μF condenser.
C_{13}.	4 μF condenser.
C_{14}.	24-μF electrolytic condenser.
C_{15}, C_{16}.	0·5-μF condenser.
C_{17}, C_{18}.	0·001-μF condenser.
C_{19}, C_{20}.	0·1-μF condenser.
C_{21}, C_{22}.	0·02-μF condenser.
C_{23}, C_{24}.	0·005-μF condenser.
C_{25}, C_{26}.	0·001-μF condenser.
C_{27}.	25-μF electrolytic condenser.
C_{28}.	0·1-μF condenser.
C_{29}.	0·05-μF condenser.
C_{30}, C_{31}, C_{32}, C_{33}	4-μF condenser.
C_{34}.	2-μF condenser.
C_{35}, C_{36}, C_{37}, C_{38}, C_{39}, C_{40}.	8-μF electrolytic condenser.

L_1, L_3, L_4, L_5, L_6.	30-H chokes.
L_2.	11·3-H iron-cored inductance with adjustable gap.
T_1.	50-volt to 5-volt 150-cycle transformer.
T_2.	Power transformer, 400/400, and 6·3-volt secondaries.
T_3.	Power transformer, 400/400, with 6·3-volt and 2·5-volt secondaries.

Valves.

V_1, V_2.	RCA 27.
V_3, V_4.	RCA 56.
V_5, V_6.	RCA 6C6.
V_7, V_8.	RCA 79.
V_9, V_{10}.	RCA 42.
V_{11}.	RCA 6C6.
V_{12}, V_{13}.	RCA 83-V.

Switches, etc.

S_1, S_2.	2-pole 9-way.
S_3, S_4.	2-pole 4-way.
S_5.	Single-pole 5-way.
S_6.	Single-pole 2-way.
S_7.	5-pole 2-way.
S_8, S_9.	2-pole 3-way.
S_{10}, S_{11}, S_{12}.	2-pole single-throw.
F.	Fuses.
P.L.1, P.L.2.	Pilot lamps.

The switching frequency may be synchronized to half the input-voltage frequency by means of the potentiometer P5. The two waves may be separated laterally by means of a further potentiometer control P3. When the switching frequency is greater than the input frequency one wave may be intensified at the expense of the other by adjustment of the potentiometer P4, whilst the same control is used to make the " half periods " equal when switching at half the input-voltage frequency.

The main amplifier (Fig. 5c).

The main amplifier employs two 42-type pentodes connected in " paraphase push-pull." Amplification is controlled by a potentiometer, P6, in the input circuit. The amplifier has a maximum gain of about 60 and a maximum output, free from appreciable distortion, of about 250 volts amplitude.

The Null Method of Measurement

In this method the difference between the intermediate and unknown voltages is amplified successively by a pre-amplifier (Fig. 5*d*) and the main amplifier (Fig. 5*c*) already described in the last Section. A 6C6-type pentode is used in the pre-amplifier, and switching in the anode circuit provides for either aperiodic or tuned amplification. The resonance frequency of the tuned circuit is adjusted to 150 cycles per sec., i.e. the network frequency. The presence of a comparatively large proportion of harmonics in the alternator output is not serious when using tuned amplification, as the amplifiers then reject all except the fundamental components of the unknown and intermediate voltages. A stepped potential-divider R46–49 controls the proportion of the input voltage that is applied to the grid of the 6C6 valve. The loading effect of this potential divider on the supply circuits is of no importance since measurements are taken only when the applied voltage has been reduced to zero.

Power Supplies (Fig. 5e)

The power supplies comprise two separate rectifier units. The power switch S11 allows the electronic relay

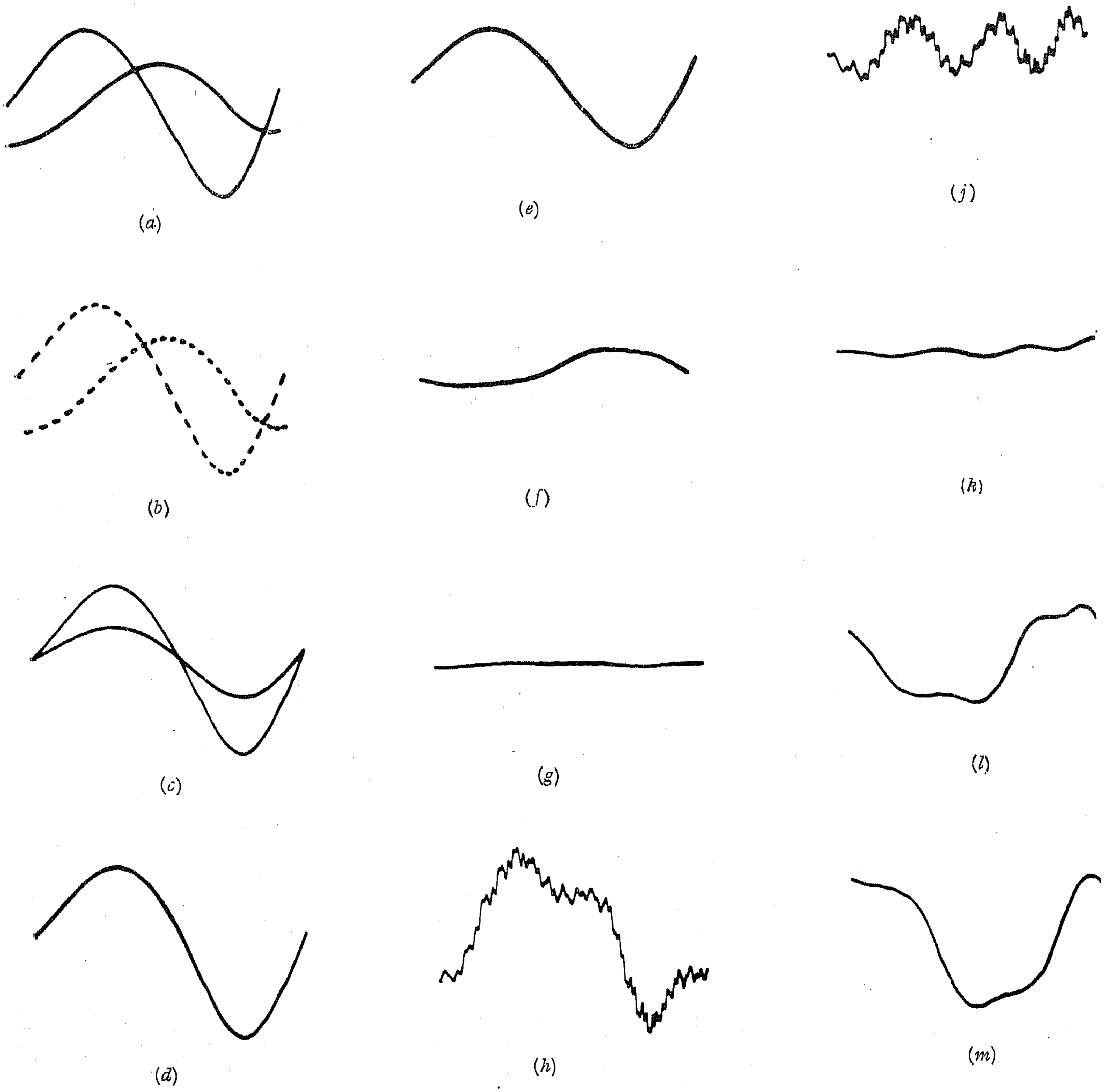

Fig. 6.—Photographic records illustrating the successive steps in the two measuring techniques.

The Coincidence Method.

(a) The unknown voltage—that with the greater amplitude—and the intermediate voltage as they appear on the screen of the cathode-ray oscillograph in the coincidence method of measurement, the electronic relay switch operating at a switching frequency equal to one-half the generator frequency.

(b) The unknown and intermediate voltages with the electronic relay switch operating at a frequency considerably higher than that of the generator.

(c) The effect of the first adjustment in the measuring procedure. The intermediate voltage has been shifted, by means of the phase-shifting transformer, from its position in (a) to that of (c) where it is in phase with the unknown voltage.

(d) The intermediate voltage has been increased in magnitude by means of the potential divider, making it equal to the unknown voltage. A readjustment of phase is sometimes necessary in order to obtain complete coincidence. Harmonics, if present, are indicated by imperfect overlapping of the two curves.

The Null Method.

(e) The difference between the unknown and intermediate voltages as applied to the cathode-ray oscillograph, after amplification, in the null method of measurement.

(f) The oscillogram after adjustment of the phase-shifting transformer to give a minimum amplitude of wave.

(g) The result of adjusting the potential divider to give a second minimum of amplitude. The oscillogram has been reduced almost to a straight line.

(h) Showing the effect of an increase in the amplification of the difference voltage. A certain amount of fundamental, together with a large proportion of harmonic, is apparent.

(j) The result of further adjustment of the phase-shifter and potential divider. The fundamental component has been removed, leaving prominent 3rd and higher-order harmonics.

(k) Showing the effect of changing from aperiodic to tuned amplification. The higher-order harmonics have been almost completely eliminated, leaving only a small amount of 3rd harmonic. Usually the entire measuring procedure is carried out using tuned amplification.

(l) Showing the effect on the oscillogram (j) of shifting the phase of the intermediate voltage by 1°.

(m) Showing the effect on the oscillogram (j) of altering the amplitude of the intermediate voltage by 1 %.

switch and twin amplifiers to be cut out of service when only the null method of measurement is being used.

(5) PHOTOGRAPHIC RECORDS (Fig. 6)

A number of oscillographic records are shown in Fig. 6. These show the various stages in the measuring procedure for the coincidence and the null methods of measurement, respectively.

(6) REMARKS AND CONCLUSIONS

In the null method of measurement the amplifiers and cathode-ray oscillograph together form a highly sensitive indicator whose function is to register the equality between the unknown and the intermediate voltages. Since this equality can be adjusted with great precision, the accuracy of the measurement must be determined mainly by the precision with which the intermediate voltage is known in terms of the standard, and this in turn depends upon the accuracy of the phase-shifter and the potential divider. These instruments can be constructed and calibrated with a high degree of precision, and great accuracy, therefore, is possible when using this method of measurement.

Quite a small cathode-ray oscillograph tube is adequate with the null method, since measurements are taken when the trace on the screen is reduced to a straight line.

With the coincidence method the accuracy depends largely upon the precision with which the two waves can be superimposed, and this is affected by (*a*) the size of the oscillograph diagram and (*b*) the harmonic content of the waves. A large screen diameter is desirable in view of (*a*). The effect of (*b*) could be reduced by inserting tuned circuits in the pre-amplifiers to the electron switch, but this would not be justified unless the harmonic content were considerably greater than 1 %.

The apparatus used in the coincidence method may at once be used for analysis of non-linear networks, the method allowing the comparison of a distorted network voltage or current with the generator e.m.f.

The equipment, with slight modifications, may also be used in the transient analysis of networks. The transient current or voltage concerned is recorded photographically, together with the changing e.m.f. which produces the transient. The electronic relay switch is operated at a frequency considerably higher than the generator frequency, so that each curve is composed of small dots. A single-sweep linear time-base provides the time scale.

The measuring equipment was designed primarily with a view to developing an analyser giving a reasonable degree of accuracy with simplicity of operation and at low cost. Each method of measurement that has been described appears to fulfil these requirements. However, the accuracy attainable with the null method makes it suitable for measurements of far greater precision than was required in its original application.

Acknowledgments

The authors were able to carry out this work in the Department of Electrical Engineering, P. N. Russell School of Engineering, University of Sydney, through their association with that Department and with the Radio Research Board of the Australian Council for Scientific and Industrial Research, and through a grant from the Commonwealth of Australia for research in Australian Universities.

The equipment was developed at the request of the Sydney County Council Electricity Undertaking and was constructed in their workshops.

The authors wish to express their thanks to Prof. J. P. V. Madsen for his continued interest and encouragement, and to Mr. A. P. Mackerras and Mr. F. H. Cureton of the Sydney County Council Electricity Undertaking for their collaboration, particularly in the calibration and testing of the equipment.

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DISCUSSION ON
"QUASI-STABLE FREQUENCY-DIVIDING CIRCUITS"*

Mr. H. Mahmoud (Egypt) (*communicated*): In working out some of the properties of the "synchronized oscillator," I found it possible to calculate the amplitude of oscillation as well as the range of synchronization by the simple means of selecting the proper terms from the expression for the anode current. The same method could be applied when the system is used for frequency division, and I think the result of such a treatment will be a useful addition to the paper.

Fig. A shows a triode having a tuned circuit in series with the synchronizing source in the anode circuit, and reaction applied to the grid circuit. The losses in the circuit are represented by a shunt arm of conductance G in order to simplify the analysis, and the results obtained apply as well to the more usual case when the losses are associated with the inductance.

Let us assume that the resonant circuit is tuned to a

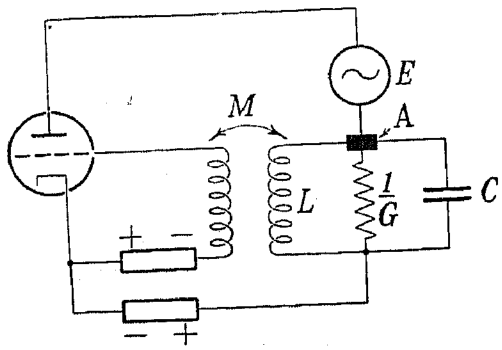

Fig. A

frequency $p/(2\pi)$, while the source has a frequency $q/(2\pi)$, where p and q are nearly equal.

Under operating conditions let the synchronizing source be represented by

$$E' = E \sin (2qt - \theta)$$

and the voltage across the tuned circuit by

$$v = V \sin \omega t$$

Since the tuned circuit discriminates strongly against frequencies far from its resonant frequency, then ω will be nearly equal to p.

The alternating component of the anode current can be approximately represented by

$$i_a = a(v_a + \mu v_g) + b(v_a + \mu v_g)^2 + c(v_a + \mu v_g)^3 \quad (1)$$

From Fig. A we find the value of $(v_a + \mu v_g)$:—

$$v_a + \mu v_g = (1 - \mu M/L) V \sin \omega t + E \sin (2qt - \theta)$$

and by substituting this value in equation (1), and selecting only those terms with angular frequencies near p, we get for the alternating component of the anode current:—

$$i_a = akV \sin \omega t + \tfrac{3}{4}ck^3V^3 \sin \omega t + 2 \cdot \tfrac{3}{4}ckE^2V \sin \omega t + bkVE \cos \left[(2q - \omega)t - \theta\right] \quad . \quad . \quad (2)$$

where $k = (1 - \mu M/L)$.

By applying Kirchhoff's law for the currents meeting at point A we get

$$-i_a = GV \sin \omega t + CV \cos \omega t - (1/\omega L) V \cos \omega t \quad (3)$$

From equations (2) and (3) it may be concluded that the frequency $(2q - \omega)$ must equal ω, or in other words the frequency of the voltage across the tuned circuit is exactly half that of the impressed voltage.

Using this result and equating terms of $\cos \omega t$ and $\sin \omega t$ separately, we find

$$VbkE \cos \theta = (V/\omega L) - \omega CV \quad . \quad . \quad . \quad (4)$$

and

$$Vk(a + \tfrac{3}{4}ck^2V^2 + 2 \cdot \tfrac{3}{4}cE^2 + bE \sin \theta) + VG = 0 \quad (5)$$

By putting $E = 0$ in equation (5) we get the case of an ordinary regenerative amplifier which will start to oscillate as soon as

$$ka + G \leq 0 \quad \text{i.e. } a(\mu M/L - 1) \geq G \quad \text{or} \quad \mu M/L \geq 1 + G/a\dagger$$

If the system is to remain stable in the absence of the synchronizing e.m.f., then the coupling should be smaller than the value indicated above, i.e.

$$\mu M/L = 1 + G/an \text{ (where } n \text{ is greater than unity)}$$

or
$$-G = an(1 - \mu M/L) = ank$$

Putting this value of G in equation (5), then

$$bE \sin \theta + \tfrac{3}{4}c(k^2V^2 + 2E^2) = a(n - 1) \quad . \quad (6)$$

The factor c in all the above equations is negative for all practical cases, and therefore we put $\tfrac{3}{4}c = -\gamma$. Equations (4) and (6) then become

$$bE \cos \theta = \left(\frac{an}{G}\right)(\omega C - 1/\omega L) = \left(\frac{an}{G}\right)(Z/\omega L) = \beta Z \quad (7)$$

$$bE \sin \theta - \gamma(k^2V^2 + 2E^2) = a(n - 1) = \alpha \quad . \quad (8)$$

where

$$Z \simeq 2\frac{\omega - \omega_0}{\omega_0},\ \omega_0^2 = \frac{1}{C},\ \beta = \frac{an}{G\omega L},\ \text{and } \alpha = a(n - 1)$$

Equations (7) and (8) give the complete behaviour of the system. Equation (7) gives the variation of the phase angle θ (between the impressed e.m.f. and a fictitious e.m.f. in phase with the output voltage but of double

† It will be seen that the factor $1/a$ is the a.c. anode resistance of the valve when working under linear conditions.

* Paper by R. L. Fortescue (see vol 84, page 693).

the frequency) when the frequency of the impressed e.m.f. is varied around a value equal to double the resonant frequency of the tuned circuit.

Equation (8) when rearranged gives the amplitude of the output voltage:—

$$V^2 = (1/\gamma k^2)[bE \sin\theta - 2\gamma E^2 - \alpha] \quad . \quad . \quad (9)$$

Therefore we see that, in general, the output will vanish unless the amplitude E lies between two values given by the roots of equation (9) when V is made zero.

We also note that if the amplitude E is held at a favourable value and the frequency is slowly varied, a point will be reached which makes $\sin\theta$ of such a value that the amplitude of the output is reduced to zero. The range over which the phase angle θ varies is thus seen to be between $\frac{1}{2}\pi$, a value less than π, and a value greater than 0.

The range over which the system will operate is then found by eliminating the angle θ from equations (7) and (8) and putting $V = 0$ in the latter. Then

$$b^2E^2 = \beta^2Z^2 + [\alpha + 2\gamma E^2]^2 \quad . \quad . \quad . \quad (10)$$

This is the equation of an ellipse and of the form of the experimental curve given in Fig. 4 (page 697 of the paper).

Had the synchronizing e.m.f. been introduced in the grid circuit instead of in the anode circuit, then equations (1) to (10) would have had to be modified by replacing E by μE.

The case considered above is for division by 2, but the method outlined applies equally well for other cases.

An alternative circuit for frequency division is shown in Fig. B. The circuit is arranged to be initially unstable, and the extra reaction is cut out as soon as an output of the required frequency is obtained.

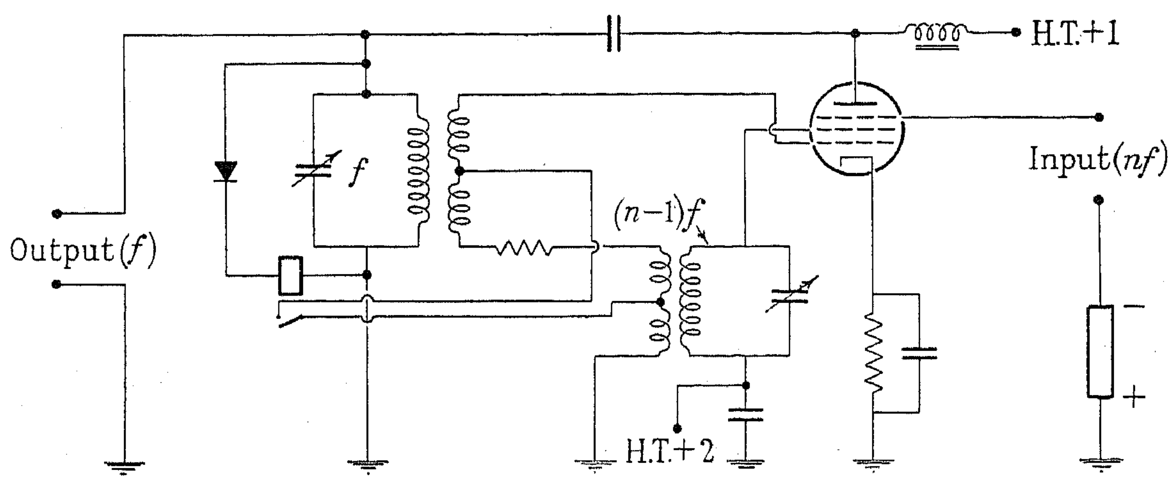

Fig. B

Mr. R. L. Fortescue (*in reply*): Mr. Mahmoud gives a steady-state analysis of a simple oscillator operating as a frequency divider and shows that quasi-stable working should be possible if direct reaction is reduced, by loosening grid-anode coupling, to a point just below the minimum required for self-oscillation. It seems, however, that this condition is difficult to obtain in practice, such an oscillator usually continuing to oscillate, once started, whether synchronizing drive is present or not; though it is easy to adjust it so that it will not *start* free oscillation without this drive. The reason for this behaviour is probably the form of the valve characteristic of the commoner valves, which either includes appreciable terms higher than the second order in v or may have a ratio $b^2/(ac)$, governing the intermodulation/direct reaction ratio, so small that the permissible range of grid coupling for quasi-stable operation is too critical to be maintained without special precautions. Even in the absence of such effects, however, the steady-state analysis may be misleading. Mr. Mahmoud assumes the voltage across the tuned circuit to be of the form $v = V \sin\omega t$, when $\omega \simeq p$. Actually such an approximation is only valid if $\omega = p$, for if the oscillator is not synchronized the voltage takes a complex form best expressed by a modulated wave $v = Vf(t)\sin pt$, there being, speaking loosely, a beat between forced and free oscillations. The steady analysis thus only gives conditions which must be satisfied if a continuous state of frequency division exists. Such conditions are necessary, but not sufficient, for the assumed equilibrium state may be an unstable one. A steady-state solution for a normal valve oscillator is obtained by putting all a.c. voltages equal to zero; but it is unstable until the reaction is reduced below a certain level. By means of isoclines it can be shown that with a simple free oscillator stable and unstable states alternate with a.c. amplitude; i.e. if the origin, where all a.c. voltages are zero, is unstable, the next steady state is stable, followed by another state with higher a.c. voltages satisfying the analysis but unstable, etc. Probably this is also true in the case of driven oscillators and frequency dividers, and a quasi-stable system would then have a stable origin and stable oscillating state separated by an unstable equilibrium of lower a.c. amplitude. To ensure that the divider settles to the stable oscillation and does not return to the stable origin, with zero a.c. output at divided frequency, the special starting system is required. It will be interesting to see whether the future produces an analytic method similar to the isocline system which can be applied to this problem of the unsynchronized divider to settle these points.

DISCUSSION ON "THE QUADRATURE TACHOMETER"*

Mr. W. Geyger (Germany) (*communicated*): In the "Introduction" the author states that he invented the quadrature tachometer in December, 1937, and that it operates on a principle believed to be new. I should like to point out, however, that this type of alternating-current tachometer, characterized by the use of a two-phase generator as supply unit and an electrodynamometer as indicating apparatus, was the subject of a specification in 1912 by Dr. G. Keinath of Messrs. Siemens and Halske, and was also fully described by him.†

Whereas direct-current tachometers (a direct-current generator with a moving-coil instrument) indicate the direction of rotation by the direction of the movement of the pointer in the indicating apparatus, alternating-current tachometers with single-phase generators do not indicate the direction of rotation. On this account Dr. Keinath introduced the alternating-current tachometer described in the above two references, a two-phase generator serving as the supply unit and an electrodynamometer as indicating apparatus, such apparatus being in the form of an iron-enclosed unipolar instrument with a scale angle of 300°. As claimed by Dr. Keinath, with this arrangement one can "also indicate the direction of rotation with alternating current and thus considerably improve the value of the instrument. . . . The accuracy which can be achieved by the use of this principle is greater than with all others. By the choice of the frequency one can eliminate all influences due to temperature, and likewise all errors due to variation of the resistance of the leads between the generator and the indicating apparatus. Now it is a small step to the use of a rotating-field instrument in place of the electrodynamic instrument, a method which gives almost the same results. Such instruments are constructed by the Pioneer Instrument Co., Brooklyn, as tachometers for use in aeroplanes. At maximum speed they operate at a frequency of 225 cycles per sec. The instrument has a disc armature of about 60 mm. diameter and a scale of 720°; that is to say, the pointer rotates twice on its axis. For this particular application this appears to be permissible, in order to increase the length of the scale without increasing the size of the instrument, as in controlling an aeroplane one could hardly be in any doubt whether the revolutions per minute are, for example, 700 or 1 400."

Dr. E. B. Brown (*in reply*): After reading the patent specification (No. 6977/1912) of Siemens and Halske referred to by Mr. Geyger, I wish to acknowledge Dr. Keinath as a prior discoverer of the principle of the quadrature tachometer. I consider, however, that the time spent in experimental work and in writing the paper was not wasted, for the following reasons:—

In the first place, the paper should have a value in emphasizing the great possibilities and accuracy inherent in the working principle of the instrument, which is not at present utilized as it deserves to be. The paper also points out the simple means of diminishing or eliminating the small temperature coefficient which remains at lower frequencies than Dr. Keinath suggests; this control of the coefficient enables the use of generators of simpler construction and lower speed, which is an advantage in some cases.

A second outcome of the experimental work has been the evolution of a very accurate and simple self-contained instrument in which the generator and indicating instrument are combined in a single unit.

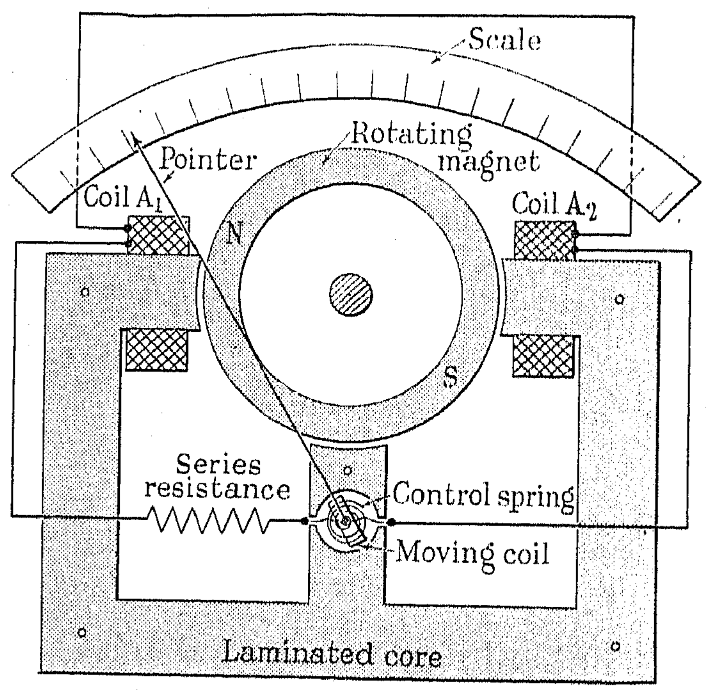

Fig. A.—Tachometer arranged for direct indication.

The novelty of this apparatus is so far unchallenged, and I have called it the quadraflux tachometer in order to distinguish it from the previously described instrument, from which it differs in respect of the form of the generator, which is single-phase, and in the manner of obtaining the quadrature flux in which the moving coil works. Fig. A is almost self-explanatory.

The generator is single-phase with a rotating magnet, and the stationary armature has two polar projections carrying the windings, which are connected to the moving coil through a high series resistance in the usual manner. The novel feature consists in situating the moving coil in a gap or gaps in an auxiliary pole midway between the main poles of the alternator. The alternating field in this auxiliary pole is thus constant in value and in quadrature with the field in the main poles, so that the

* Paper by Dr. E. B. Brown (see vol. 84, page 499).

† G. Keinath: "Die Technik elektrischer Messgeräte," 3rd edn., vol. 2, pp. 295–297, published by R. Oldenbourg (Munich and Berlin), 1928; also G. Keinath: "Elektrische Drehzahlmesser," *Archiv für Technisches Messen* (*ATM*), Sheet J 162–1 (March, 1935), published by R. Oldenbourg (Munich and Berlin).

coil is situated in an alternating field which is substantially in phase with the current flowing in the coil. Thus a linear scale is obtained and a negligible temperature coefficient. A multi-range instrument is readily obtained by alteration of the resistance in series with the coil.

In conclusion, I tender my apologies for the omission from the paper of an acknowledgment to the University of Melbourne for the provision of a research grant enabling the experiments to be carried out in the Engineering School of the university. I should also like to acknowledge the valuable help of the staff of the Electrical Engineering Department and the co-operation of the engineering workshop of the university.

THE PLANNING OF STREET LIGHTING*

By J. BERTRAM, B.Sc., Graduate.†

(ABSTRACT *of paper read before the* SOUTH MIDLAND STUDENTS' SECTION, *at* BIRMINGHAM, 28*th March*, 1938.)

INTRODUCTION

During the last decade there has been a revolution in street lighting all over our country. From a business which local councils tended to regard as a side issue, it has grown to one of the first order of technical and commercial importance. Along with its development there has grown a more thorough appreciation of the principles involved in this creation of artificial visibility, and this had led to more and more investigational work.

The need for safety on the roads is focusing a critical public interest on the lighting of our streets and highways, and the final recognition of the need for development in this line was the appointment by the Ministry of Transport of a Departmental Committee on Street Lighting. Nowadays practically every borough electrical engineer and his assistants are finding that they have to face the problem of lighting their streets satisfactorily—a problem with many baffling complexities.

The subject of street lighting is so vast that it can only be touched on in one paper. This paper, therefore, will give a very brief summary of the technical aspect of the street-lighting problem, and will collect together the various factors which control the planning of a good installation.

TYPE OF UNIT

There are prevalent to-day two main types of electric light source:—

(*a*) Electric filament lamps.
(*b*) Electric discharge lamps.

It can be said with a considerable amount of truth that the arrival of the discharge lamp was the biggest incentive to the rise in technical importance of street-lighting problems.

The change in the type of unit used is probably least noticeable with filament lamps, although striking advances can be found in America, where the introduction of a bi-post filament lamp has brought out the Reid Channon stepped reflector lantern.

Consideration of the polar distribution of a standard 400-watt mercury discharge lamp shows that for efficient illumination, whether the lamp is operated horizontally or vertically, more than half the light output from the lamp will have to be re-directed. There are only two effective methods of re-directing light, viz. reflection and refraction. Lanterns for discharge lamps employ some combination or other of these two methods. A modern design is shown in Fig. 1.

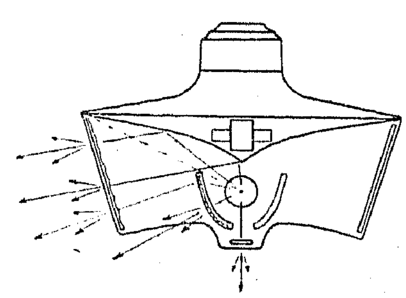

Fig. 1

With the vertical lamps the source has its greatest dimensions in the plane of major re-direction. For accurate re-direction of light the source should have the smallest possible dimensions, and the disadvantage of vertically-operated discharge lamps is evident. Accurate control can only be obtained by a considerable sacrifice in efficiency.

If, however, the discharge lamp is operated horizontally, the smallest dimension of the source (which is the cross-section of the luminous arc) lies in the plane of major re-direction, and accurate control can therefore be obtained by using an optical system of normal size and shape. Also the horizontally burning lamp gives roughly the required rectangular distribution in the horizontal plane, so that very little re-direction will be necessary.

The efficacy of horizontal operation, first advocated in

* The original paper, of which this is an abstract, was awarded a Students' Premium by the Council.
† British Thomson-Houston Company, Ltd.

1934,* has now been proved by the general trend in street-lighting practice.

VISIBILITY

This is the quality of being seen clearly by the eye. To fulfil its requirements it is necessary to illuminate the road surface so that the darkest object can be seen upon it at a considerable distance. This is generally obtained by making use of the fact that road surfaces have a high specular reflectivity value at glancing angles of incidence and, therefore, do not need to be flooded with excessive quantities of light. The problem is entirely different from that of lighting a room or a factory area.

The whole problem was never seriously investigated until the Ministry of Transport set up a Departmental Committee to consider it. The main theme of their report discusses in turn each of the essential points. Their recommendations for main-road lighting have been briefly summarized as follows:

Mounting Height.—25 ft.

Spacing.—120–150 ft. with permissible maximum of 180 ft. It is noted that at bends, road junctions, etc., this spacing may need to be appreciably lower.

Overhang.—The maximum should be 6 ft. The maximum distance between two rows of sources should be 30 ft. With roads wider than 40 ft. lanterns should be kerb-mounted, and additional sources should be placed centrally at intervals not exceeding 35 ft. in length.

Siting.—This is obtained by limiting the angle subtended at the observer by sources which appear to be adjacent. Angular limits will vary to some extent with the nature of the road surface. The Committee do not make any rigid rules concerning siting, but give a number of very useful recommendations.

Lantern Power.—Broadly speaking, this is the output from the lantern. The Committee suggest 3 000 to 8 000 lumens per 100-ft. run. With 150-ft. spacing this means a lantern output of 9 500 to 12 000 lumens.

Distribution and Glare.—The Committee make no definite recommendations.

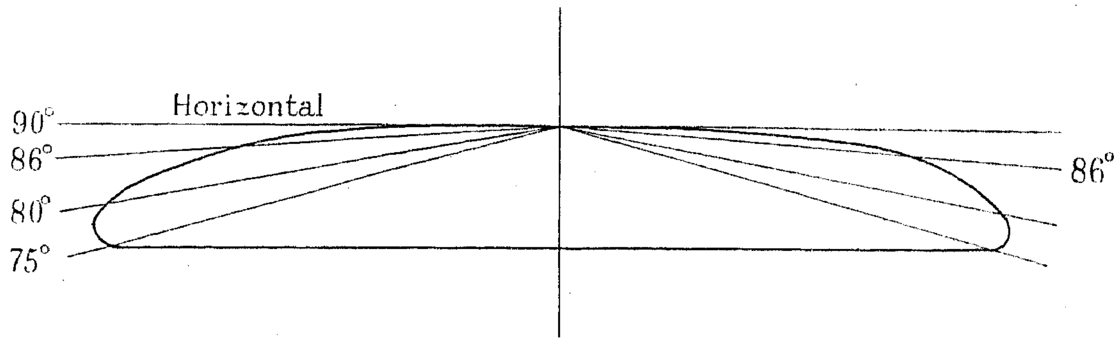

Fig. 2.—Curve representing an ideal form of lantern distribution.

At the present time there are three distinct types of distribution in use:—

(1) Non-cut-off.
(2) Controlled cut-off.
(3) Full cut-off.

Controlled cut-off is a recent innovation. The concentration of high candle-power near to the horizontal to effect high road brightness results in heavy glare from all the lanterns visible ahead of the observer. This glare can be reduced by taking advantage of the rapidly increasing road reflectivity by cutting down the candle-power as the horizontal is approached. The polar curve of such a lantern for 150-ft. spacings will have its maximum at 75° to 80°, maintaining a fairly high level up to 86° and then rapidly decreasing towards 90°. Such a curve is shown in Fig. 2. The author feels that this controlled cut-off gives the vital compromise necessary between road brightness and glare.

* R. Maxted and L. J. Davies: *Electrical Review*, 1934, vol. 115, p. 111.

INSTITUTION NOTES

LIST OF MEMBERS

A new list of members, corrected to the 1st September, 1939, is in preparation and will be published about the end of November. Any member wishing to receive a copy should apply to the Secretary.

I.E.E. REGULATIONS FOR THE ELECTRICAL EQUIPMENT OF SHIPS

A revised Edition (Third Edition) of the I.E.E. Regulations for the Electrical Equipment of Ships has been published.

Copies may be purchased from the publishers (Messrs. E. and F. N. Spon, Ltd., 57 Haymarket, London, S.W.1), or at the offices of The Institution, at the following prices:—

Bound in cloth:	3s. net (or 3s. 3d. post free).
Bound in paper covers:	2s. net (or 2s. 2d. post free).

THE PAGE PRIZE

The Page Prize for 1938–39 has been awarded to Mr. O. H. Hosking for his thesis entitled "Aerial Warfare and the Maintenance of Electricity Supplies."

ACTIVITIES OF THE INSTITUTION

The following is a copy of the circular which was enclosed to every member with the October issue of the *Journal* (see page 566 of "Institution Notes" in that issue):—

Institution Activities

It has been decided by the Council that as many as possible of the activities of The Institution should be carried on during the period of the war in the same way as hitherto, and that the Library and Headquarters of The Institution should remain for the time being in the present building at Savoy Place, W.C.2. The Library and Office hours will remain unchanged until Saturday, 21st October, 1939, after which they will be as follows:—

From 23rd October until 18th November: 9.30 a.m. to 5 p.m. (Saturdays 9.30 a.m. to 12.30 p.m.).

From 20th November until further notice: 9 a.m. to 4.30 p.m. (Saturdays 9 a.m. to 12 noon).

Cancellation of Meetings

The Council, with considerable reluctance, have felt it advisable to cancel all meetings that were to have been held in London for the reading and discussion of papers during the first half of the Session, and the only meetings to be held will be two formal Ordinary Meetings, details of which are given below, for the election and transfer of members in accordance with the provisions of the Bye-laws.

The Committees of the Local Centres and Sub-Centres have also, except in one or two instances, temporarily suspended their local programmes.

As an alternative to meetings a complete list of the papers that were to have been read will be issued to members at the end of October intimating that advance copies can be obtained on application to the Secretary and that the submission of written comments on any papers will be welcomed with a view to publication in the *Journal* in the form of discussion, with the author's reply, when the paper itself is published in due course. By this means it is hoped to continue to provide material for the *Journal* on the same lines as hitherto.

Copies of the Presidential Address, which was to have been delivered by Mr. Johnstone Wright at the Opening Meeting in London on 26th October, will be circulated to all members when the list referred to in the preceding paragraph is issued.

The foregoing arrangements will apply in respect of all papers that were to have been read at Ordinary Meetings in London and at meetings of the Wireless, Meter and Instrument, and Transmission Sections. The programme of Informal Meetings and the meetings of the London Students' Section as well as all social functions for senior members have also been suspended, but it is hoped that a small number of visits to works and at least one social function will be found possible during the Session for members of the Students' Section.

As regards activities in the provinces, if any Centre, Sub-Centre, or Students' Section is able to carry out a programme of meetings, visits, and functions, separate notification will be made to the local members in the usual way.

Associate Membership Examination

As already announced the Associate Membership Examination arranged for November next will take place, and it is hoped that it will be found practicable to continue to hold this Examination at the usual intervals in future.

Journal

It is essential that the interchange of ideas and technical information should be maintained, and with this object the Council hope that members who have had under consideration or in preparation papers with a view to submission for reading at meetings or for publication in the *Journal* without being read at meetings, will continue their work upon them and submit them in due course. It is recognized that many members may not in present circumstances be able to prepare extensive papers, and the Council would be pleased to have the support of those who are in a position to offer short papers of limited scope or summarized accounts of the results of work which would normally have provided material for a full-length paper.

ORDINARY MEETINGS

The following purely formal Ordinary Meetings will be held in London on the dates stated in order to comply with the Bye-laws relating to the election and transfer of members:—

Ordinary Meeting, Thursday, 26th October, 1939, *at twelve-thirty p.m.*, in the I.E.E. Lecture Theatre, Savoy Place, W.C.2 (for the suspension of a list of names of applicants for election and transfer approved by the Council).

Ordinary Meeting, Thursday, 16th November, 1939, *at twelve-thirty p.m.*, in the I.E.E. Lecture Theatre, Savoy Place, W.C.2 (for the purpose of carrying out a ballot in respect of the names suspended at the meeting on the 26th October).

(NOTE.—Only Corporate Members and Associates are eligible under the Bye-laws to participate in the ballot.)

CENTRAL REGISTER

The attention of members is drawn to the statement on the above subject which appears in the October number of the *Journal* (see "Institution Notes," p. 566).

GENERAL POLICY

The general policy of the Council outlined above will be followed until the New Year, with any additional activity that may be found practicable from time to time. The whole question will be reviewed towards the end of this year in the light of the circumstances then prevailing, and if it is at all possible the Council hope to arrange at least a skeleton programme of meetings to be held during the second half of the Session.

Many members have already taken up their duties with the active forces of the Crown, while the remainder are directing their energies in the important role which electricity must play in the general national effort. To all, the President and Council express the hope of an early conclusion of the conflict which has been forced upon the nation and the resumption of the normal peace-time work and progress of our profession.

W. K. BRASHER,
Secretary.

16th October, 1939.

PROCEEDINGS OF THE METER AND INSTRUMENT SECTION

83RD MEETING OF THE METER AND INSTRUMENT SECTION, 3RD FEBRUARY, 1939

Captain B. S. Cohen, O.B.E., Chairman of the Section took the chair at 7 p.m.

The minutes of the meeting held on the 6th January, 1939, were taken as read and were confirmed and signed.

The following papers were read and discussed: "The Electrical Protection of Cold-Cathode Luminous Discharge-Tube Installations" (see page 295), by Dr. H. M. Barlow, Associate Member; and "An Electrostatic Analyser for Complex Waves of Small Amplitude" (see page 302), by Prof. J. C. Prescott, D.Eng., Associate Member. Demonstrations of apparatus were given in connection with both papers.

A vote of thanks to the authors, moved by the Chairman, was carried with acclamation.

84TH MEETING OF THE METER AND INSTRUMENT SECTION, 3RD MARCH, 1939

Captain B. S. Cohen, O.B.E., Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 3rd February, 1939, were taken as read and were confirmed and signed.

A paper by Mr. D. C. Gall, entitled "A Review of the Design and Use of Potentiometers" (see page 516), was read and discussed. A demonstration of apparatus was given in connection with the paper.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

85TH MEETING OF THE METER AND INSTRUMENT SECTION, 24TH MARCH, 1939

Captain B. S. Cohen, O.B.E., Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 3rd March, 1939, were taken as read and were confirmed and signed.

An informal discussion, opened by Messrs. C. W. Hughes and G. F. Shotter, took place on "Relative Merits of Methods of Testing Meters for Certification." Messrs. Hughes and Shotter replied to the discussion.

Messrs. E. H. Miller and G. F. Shotter then opened a discussion on "Should Legislation be invoked to decide the Position of Meters on Consumers' Premises?" Messrs. Miller and Shotter replied to the discussion.

A vote of thanks was, on the motion of the Chairman, accorded to the openers of the discussions and was carried with acclamation.

86TH MEETING OF THE METER AND INSTRUMENT SECTION, 14TH APRIL, 1939

Captain B. S. Cohen, O.B.E., Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 24th March, 1939, were taken as read and were confirmed and signed.

A paper by Mr. G. F. Shotter, Member, entitled "A Critical Survey of American Metering Practice," was read and discussed.

A vote of thanks to the author, moved by the Chairman, was carried with acclamation.

87TH MEETING OF THE METER AND INSTRUMENT SECTION, 5TH MAY, 1939

Captain B. S. Cohen, O.B.E., Chairman of the Section, took the chair at 7 p.m.

The minutes of the meeting held on the 14th April, 1939, were taken as read and were confirmed and signed.

The Chairman announced that the following members had been nominated to fill the vacancies which would occur on the Committee on the 30th September, 1939:—

Chairman: F. E. J. Ockenden.

Vice-Chairman: C. W. Marshall, B.Sc.

Ordinary Members of Committee: A. H. M. Arnold, Ph.D., D.Eng., A. T. Dover, L. B. S. Golds, A. E. Jepson, E. W. Moss, and S. H. Richards.

In the event of a ballot for the new Committee being

required, Messrs. F. O. Barralet and L. J. Matthews were appointed scrutineers.

Mr. D. A. Oliver then delivered a Lecture on " Permanent Magnets for Integrating and Deflectional Instruments. "

A vote of thanks to the lecturer, proposed by Mr. F. E. J. Ockendend and seconded by Mr. A. Felton, was carried with acclamation.

MEMBERS ON SERVICE WITH H.M. FORCES (FIRST LIST)

[NOTE.—The Secretary will be glad to receive, for publication in subsequent lists, the names of other members of The Institution who are serving with His Majesty's Forces, together with particulars of their rank and the unit in which they are serving.

It is also proposed to publish lists of promotions, transfers, military honours awarded, etc. All such particulars, both in regard to a member himself and in connection with other members of whom he may have knowledge, should be sent to the Secretary as early as possible so that the Institution records can be kept up to date.]

Members

Name	*Corps, etc.*	*Rank*
de Burgh, D. H.	Royal Air Force	Wing-Comdr.
Evans, C. H. S.	Royal Engineers	Colonel
Grover, C. A.	Royal Engineers	Lieut.-Col.
Harris, E. H. C.	Royal Signals	Major
Hewson, F. T.	Royal Navy	Commander
Hogg, D. B.	Royal Artillery	2nd Lieut.
Kennedy-Purvis, Sir C. E.	Royal Navy	Vice-Admiral
Leeson, B. H.	Royal Engineers	Lieut.-Col.
McHaffie, H. G.	Royal Engineers	Captain
Manning, F. E. A.	Royal Signals	Lieut.-Col.
Rawll, R. H.	Royal Artillery	Major
Williamson, G. W.	Royal Air Force	Wing-Comdr.

Associate Members

Name	*Corps, etc.*	*Rank*
Adye, A. F. C.	Royal Artillery	Captain
Ainley, P. E.	Royal Army Ordnance Corps	Lieutenant
Allerston, P.	Royal Air Force	Flying Officer
Anderson, J. R.	Royal Engineers	Major
Baldwin, K. B.	Royal Signals	2nd Lieut.
Barford, F. C.	Royal Army Ordnance Corps	Lieutenant
Barnett, H. E.	Royal Army Ordnance Corps	Lieutenant
Baynton, R. A.	Royal Engineers	Captain
Beavis, C. J.	Royal Artillery	Gunner
Beck, W. L.	Royal Signals	Captain
Beyts, W. D. H.	Royal Engineers	Major
Blackburn-Maze, L. N.	Royal Naval Volunteer Reserve	Sub-Lieut.
Blair, D. C.	Royal Signals	2nd Lieut.
Booth, C. F.	Royal Signals	Captain
Brazier, C. C. H.	Royal Engineers	Lieut.-Col.
Brett, S. I.	Royal Signals	Captain
Brown, C. N.	Royal Artillery	Major
Browne, A. H.	Royal Navy	Lieut.-Comdr.
Bullard, C.	Royal Army Ordnance Corps	Major
Caley, L. P.	Royal Naval Volunteer Reserve	Sub-Lieut.
Champion, C. H.	Royal Naval Volunteer Reserve	Sub-Lieut.
Chaytor, J. C.	Royal Artillery	Captain
Clarke, H. M.	Royal Artillery	Major
Cocks, A. H. W. J.	Royal Air Force	Squadron Leader
Collis, W. B. G.	Royal Signals	Captain
Costelloe, W. H. G.	Royal Engineers	Brevet Lieut.-Col.
Cramer, D. H. J.	Royal Army Ordnance Corps	Lieutenant
Crook, W. E.	Royal Air Force	Flight-Lieut.
Cubitt, R. H.	North Somerset Yeomanry	Corporal
Daniel, F. J.	Royal Army Ordnance Corps	Lieutenant
Darby, J. F.	Royal Signals	Lieut.-Col.
Denman, H. L.	Royal Navy	Lieutenant
Drummond, B. G.	Royal Engineers	Captain
Drury, G. J. S.	Royal Engineers	Captain
Dryland, L. W. J.	Royal Signals	Captain
Dudley, H.	Royal Signals	2nd Lieut.
Edes, N. H.	Royal Signals	Major
Edgecombe, P. J. E.	Royal Engineers	Captain
Elford, E. N.	Royal Engineers	Major
Evens, H. W.	Royal Air Force	Group Captain
Everitt, R. A.	Royal Navy	Lieut.-Comdr.
Fairthorne, R. B.	Royal Navy	Lieut.-Comdr.
Faragher, A. J.	Royal Engineers	Sapper
Farthing, G. A.	Royal Signals	2nd Lieut.
Fayle, L. R. E.	Royal Engineers	Captain
Fisher, B. J.	Royal Navy	Commander
Fordham, H. M.	Royal Engineers	Colonel
Garnett, C. V. H.	Royal Engineers	Major
Glanister, C. W.	Royal Engineers	Lieutenant
Goddard, L.	Royal Signals	Major
Graham, A. G.	Auxiliary Air Force	A.C.2
Green, R. A.	Royal Signals	Lieutenant
Gurnhill, J. B.	Royal Engineers	Major
Harding, R. J.	Royal Army Ordnance Corps	Lieutenant
Harnden, A. B.	Royal Signals	2nd Lieut.
Hartley, W. G. B.	Royal Navy	Commander
Hawkins, R. C.	Auxiliary Air Force	Acting Pilot Officer
Hext, F. M.	Royal Engineers	Major
Highway, F. G.	Royal Engineers	Major
Horgan, M. O.	Royal Engineers	Captain
Hughes, H. M.	Royal Artillery	Lieutenant
Hunter, C. M.	Royal Army Ordnance Corps	Lieutenant
Huntley, R. J.	Royal Army Ordnance Corps	Captain
Jackson, G. E.	Royal Army Ordnance Corps	Lieutenant
Keelan, R. E.	Royal Engineers	Lieut.-Col.
Keevil, L. G. M.	Royal Engineers	Major
Kennedy, J. R.	Royal Engineers	Lieut.-Col.
Kerr, A. N. D.	Royal Engineers	Staff Sergeant Mechanist
Knights, A. E.	Royal Norfolk Regiment	Major
Lanyon, G. W.	Royal Army Ordnance Corps	Lieutenant
Lendrum, H. L.	Royal Engineers	Captain
McCleery, D. K.	Royal Navy	Lieutenant
McDonald, A.	Royal Signals	Captain
McLaren, J. T.	Royal Artillery	Lieutenant
Mallinson, G.	Royal Artillery	Brevet Colonel
Minter, J. H. C.	Royal Navy	Commander
Mohring, A. J. G.	Royal Artillery	Major
Morduch, O.	Honourable Artillery Company	Gunner
Morecombe, W. M. M.	Royal Engineers	Major
Mountbatten, The Rt. Hon. Lord Louis	Royal Navy	Captain
Newman, P. L.	Royal Engineers	2nd Lieut.
Norfolk, L. W.	Sherwood Foresters	Lieutenant

Name	Corps, etc.	Rank
Norfolk, T. L.	Royal Engineers	Lieut.-Col.
Olver, G. C.	Royal Artillery	Major
Ottmann, P. A.	Royal Artillery	Captain
Parnall, E. J.	Royal Engineers	Major
Pitcairn, A. C.	Royal Signals	2nd Lieut.
Pollard, S. M.	Royal Army Ordnance Corps	Lieutenant
Potts, F.	Royal Naval Volunteer Reserve	Sub-Lieut.
Pound-Corner, H. S.	Royal Engineers	Lieutenant
Read, A. H.	Royal Signals	Lieut.-Col.
Rheam, G. T. T.	Royal Army Ordnance Corps	Lieutenant
Roberts, W.	Royal Artillery	Major
Robinson, C. V.	Royal Navy	Lieut.-Comdr.
Rogers, H. H.	Royal Navy	Lieut.-Comdr.
Sadler, E. H.	Royal Engineers	Major
Sanderson, W. T.	Royal Engineers	Sapper
Shaw, S.	Royal Artillery	Captain
Smith, A. G.	Royal Signals	2nd Lieut
Sproull, A. W.	Royal Engineers	Lieut.-Col.
Stanton, E. P.	Royal Signals	Lieutenant
Stockings, T.	Royal Engineers	2nd Lieut.
Sykes, A. C.	Royal Signals	Colonel
Taplin, A. E. H.	Royal Army Ordnance Corps	Lieutenant
Taylor, P. H.	Royal Army Ordnance Corps	Lieutenant
Thompson, D. H. H.	Royal Navy	Commander
Thurner, W. M. F.	Royal Engineers	Sapper
Turnbull, J. C.	Royal Naval Volunteer Reserve	Sub-Lieut.
Vereker, H. C.	Royal Air Force	Captain
Verity, A. S.	Royal Engineers	2nd Lieut.
Walker, G. N.	Royal Engineers	Major
Walsh, L. H.	Royal Engineers	Captain
Walton, W. F. J.	Royal Naval Volunteer Reserve	Sub-Lieut.
Warren, J.	Royal Army Ordnance Corps	Lieut.-Col.
White, H. E.	Royal Engineers	2nd Lieut.
Whitmore, G.	Royal Engineers	Captain
Wickham, E. T.	Royal Navy	Captain
Wield, R. C.	Royal Navy	Lieut.-Comdr.
Williams, H. J.	Auxiliary Air Force	Flying Officer
Wood, P. T.	Royal Engineers	Captain
Woolley, T. G.	Royal Engineers	Captain
Yates, A. V. S.	Royal Navy	Lieut.-Comdr.

Associates

Name	Corps, etc.	Rank
Cope, W. J. L.	Royal Engineers	Captain
Leeds, R. J.	Royal Engineers	Major
Maddocks, W. A.	Royal Artillery	Captain
Ray, J. C.	Royal Engineers	Lieutenant
Reed, A. W.	Royal Army Ordnance Corps	Captain
Savage, J. A.	Royal Engineers	Captain
Shearer, J.	Royal Engineers	Lieutenant
Springate, F.	Royal Engineers	Major
Thompson, V. C.	Royal Engineers	2nd Lieut.
Walton, E. S.	Artists Rifles	Corporal

Graduates

Name	Corps, etc.	Rank
Anderson, E.	Royal Engineers	Lieutenant
Barton, R. J	Royal Army Ordnance Corps	Captain
Bentley, R. D.	Royal Engineers	2nd Lieut.
Botting, E. L.	Royal Engineers	Major
Bousfield, R. H.	Royal Engineers	Sapper
Brand, N. F.	Royal Tank Regiment	Private
Brewster, H. G.	Royal Signals	Signalman
Brooks, H. W.	Royal Naval Volunteer Reserve	Sub-Lieut.
Buck, J.	Royal Artillery	Lance-Bdr.
Burgess, A. J.	Royal Army Ordnance Corps	Lieutenant
Calver, W. H.	Royal Army Ordnance Corps	Corporal
Cannell, J. A.	Royal Indian Army Service Corps	2nd Lieut.
Carmichael, I.	Royal Army Ordnance Corps	Lieutenant
Castellan, G. E.	Royal Engineers	Corporal
Clayton, K. B.	Royal Naval Volunteer Reserve	Sub-Lieut.
Coleman, W. J.	Royal Navy	Chief Electrical Artificer
Coles, R. G. H.	Royal Signals	2nd Lieut.
Connerton, C. D.	Royal Air Force	Flying Officer
Copinger, W. P.	Royal Air Force	Pilot Officer
Crawshaw, G.	Royal Signals	Signalman
Davy, G. V.	Royal Army Ordnance Corps	Lieutenant
Dawson, R. G.	Argyll and Sutherland Highlanders	2nd Lieut.
Earl, J. W.	Royal Air Force	Sergeant
Edgcumbe, P. R.	Royal Lancers	2nd Lieut.
Eldred, E.M.	Royal Air Force (V.R.)	Flt.-Lieut.
England, A. K.	Royal Engineers	Sapper
Evans, J. V.	Royal Naval Volunteer Reserve	Temporary Sub-Lieut.
Fahey, G.	Royal Army Ordnance Corps	Lieutenant
Follenfant, J. L.	Royal Engineers	Sapper
Fortnam, G. W.	Royal Army Ordnance Corps	Lieutenant
Foss, G. H.	Royal Air Force	Squadron Leader
Gallop, P. J.	Royal Artillery	Gunner
Gamble, G. A. H.	Royal Army Ordnance Corps	Lieutenant
Gardner, A. J.	Royal Naval Volunteer Reserve	Sub-Lieut.
Gill, M.	Royal Army Ordnance Corps	Lieutenant
Gimson, D.	Royal Naval Volunteer Reserve	Sub-Lieut.
Gooud, W. R.	Royal Naval Volunteer Reserve	Sub-Lieut.
Gorman, M. E.	Royal Army Ordnance Corps	Lieutenant
Greening, C. E.	Royal Artillery	Gunner
Grout, E. J.	Royal Army Ordnance Corps	Lieutenant
Hammersley, C.	Royal Engineers	2nd Lieut.
Harding, G. R.	Royal Engineers	2nd Lieut.
Hewett, B. S.	Royal Signals	2nd Lieut.
Hickox, W. F.	Royal Signals	Lieutenant
Hill, E.	Royal Engineers	Lance-Corporal
Hopkinson, A. F.	Royal Army Ordnance Corps	Lieutenant
Hopkinson, C. F.	Royal Army Ordnance Corps	Lieutenant
Johnson, H. B.	Royal Engineers	2nd Lieut.
Kassell, E. D.	Royal Engineers	2nd Lieut.
Kennion, W. R.	Royal Engineers	Brevet Major
Kitchens, H.	Royal Navy	Warrant Telegraphist
Laflin, H. E.	Royal Army Ordnance Corps	Lieutenant
Lambert, G. K.	Royal Artillery	Gunner
Lavarack, T. V.	Royal Naval Volunteer Reserve	Sub-Lieut.
Linsell, R. F.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
Livesey-Farr, A.	Royal Signals	2nd Lieut.
Livock, F. R.	Royal Artillery	Captain
Logan, T. B.	Royal Naval Volunteer Reserve	Sub-Lieut.
Mackenzie, D. H. A.	Royal Army Ordnance Corps	Lieutenant
Martin, T. G.	Royal Engineers	2nd Lieut.

Name	Corps, etc.	Rank
Mather, W. H.	Durham Light Infantry	Major
Meikle, J. C.	Royal Army Ordnance Corps	Lieutenant
Mellor, J. F. M.	Royal Army Ordnance Corps	Major
Millar, J. B.	Royal Army Ordnance Corps	Private
Milway, J. T.	Royal Army Ordnance Corps	Lieutenant
Morgan, P. A.	Royal Army Ordnance Corps	Lieutenant
Pillinger, E. W.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
Plews, H. H.	Royal Army Ordnance Corps	Lieutenant
Pontifex, C. E. C.	Royal Engineers	Sapper
Preston, G. N.	Royal Army Ordnance Corps	Lieutenant
Radcliff, R. H.	Royal Tank Regiment	2nd Lieut.
Rees, R. C.	Royal Engineers	Lieutenant
Reeves, E.	Royal Army Ordnance Corps	Lieutenant
Rhodes, J. B.	Royal Engineers	Sapper
Rice, N. R.	Royal Naval Volunteer Reserve	Sub-Lieut.
Rice, R. H. G.	Royal Air Force	Aircraftman
Richardson, J. G.	Royal Engineers	2nd Lieut.
Richardson, R. F.	Royal Engineers	Sapper
Richmond, F. A.	Royal Engineers	2nd Lieut.
Riddell, W. F.	Royal Naval Volunteer Reserve	Sub-Lieut.
Roper, A. J. H.	Royal Engineers	2nd Lieut.
Rustin, M. E.	Royal Army Ordnance Corps	Lieutenant
Sanders, K. L.	Royal Signals	Lieutenant
Saunders, J. M.	Royal Army Ordnance Corps	Lieutenant
Searle, K. A.	Royal Army Ordnance Corps	Lieutenant
Sellar, J. A.	Royal Army Ordnance Corps	Lieutenant
Shone, A. B.	Royal Army Ordnance Corps	Lieutenant
Smith, D. J.	Royal Army Service Corps	Captain
Smithson, N. W.	Royal Artillery	2nd Lieut.
Sowry, J. H. M.	Royal Navy	Lieutenant
Stevens, F. G.	Royal Naval Volunteer Reserve	Sub-Lieut.
Swift, G. P.	Royal Engineers	Captain
Tatham, F. E.	Royal Army Ordnance Corps	Lieutenant
Taylor, H. S.	Royal Naval Volunteer Reserve	Sub-Lieut.
Terrell, B. J.	Royal Engineers	2nd Lieut.
Tessier, R. L. C.	Royal Naval Volunteer Reserve	Sub-Lieut.
Thomas, A. J. K.	Royal Signals	Signalman
Thorns, G. H.	Royal Army Ordnance Corps	Lieutenant
Threlfall, A. J. C.	Royal Signals	2nd Lieut.
Tufnell, R. M.	Royal Engineers	2nd Lieut.
Varley, L. J.	Royal Signals	Signalman
Wakefield, J. A.	Royal Engineers	Sapper
Walker, D. W.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
Walker, T. G.	Royal Engineers	2nd Lieut.
Ward, T.	Royal Army Ordnance Corps	Lieutenant
Wesley, A. C.	Royal Artillery	Gunner
Whitty, W. H. R.	Auxiliary Air Force	Pilot Officer
Wilkinson, E. J.	Royal Artillery	Sergeant
Williams, N. L.	Royal Engineers	Staff Sergeant Mechanist
Wire, G. H.	Royal Artillery	Lieutenant
Wolff, E. H.	Royal Naval Volunteer Reserve	Sub-Lieut. (E)
Wright, J. D.	Royal Artillery	Gunner
Yeadon, R.	Royal Army Ordnance Corps	Lieutenant

Students

Bolton, T. G. B.	Royal Artillery	2nd Lieut.
Brodie, D. A. M.	Royal Engineers	Sapper
Cartwright, A. E.	Royal Army Ordnance Corps	Private
Collinson, W. F. P.	Royal Army Ordnance Corps	Private
Eden, J. F. G.	Royal Air Force	Leading Aircraftman
Francis, S. W.	Royal Navy	Engineer
Hitch, F. A. N.	Royal Engineers	Lieutenant
Houlton, E. M.	Royal Signals	Lance-Corporal
Lott, T. M.	Royal Air Force	Aircraftman
Pearce, W. B.	Royal Artillery	2nd Lieut.
Samuels, J. G. F.	Royal Signals	2nd Lieut.
Sigee, E.	Royal Army Ordnance Corps	Staff Sergeant

Institution Staff

Arnold, G.	Royal Air Force	A.C.2
Blanchard, E. A.	Royal Artillery	Lance-Sergeant
Francis, R. B. G.	Royal Navy	Lieut.-Comdr.
Ives, G.	Royal Signals	Signalman
Stanton, J.	Royal Naval Volunteer Reserve	Ord. Telegraphist

ACCESSIONS TO THE REFERENCE LIBRARY

[NOTE.—The books cannot be purchased at The Institution; the names of the publishers and the prices are given only for the convenience of members; (*) denotes that the book is also in the Lending Library.]

ADMIRALTY, THE. Admiralty handbook of wireless telegraphy. 2 vol. 4to. (London: H.M. Stationery Office, 1939.) (*)

vol. 1, Magnetism and electricity. 4s.
vol. 2, Wireless telegraphy theory. 6s.

ALLCOCK, H. J., *M.Sc.*, and JONES, J. R., *M.A.* The nomogram. The theory and practical construction of computation charts. 2nd ed. 8vo. viii + 224 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1938.) 10*s*. 6*d*. (*)

ARDENNE, M. v. Cathode-ray tubes. Translated by G. S. McGregor in collaboration with R. C. Walker. 8vo. xiii + 530 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1939.) 42*s*. (*)

BAUDOUX, P. L'antenne rayonnante. Institut Belge de Recherches Radioscientifiques, vol. 7. 8vo. 235 pp. (Paris: Gauthier-Villars et Cie., 1938.) 40 *francs*.

BEYAERT, R. Les petits moteurs électriques. 8vo. vi + 218 pp. (Paris: Dunod, 1939.) 98 *francs*.

BROWN, O. F., *M.A.*, and GARDINER, E. L. The elements of radio-communication. 2nd ed. 8vo. vii + 551 pp. (Oxford University Press, 1939.) 16*s*. (*)

BRÜCKMANN, H., *Dr.-Ing.* Antennen: ihre Theorie und Technik. 8vo. xiv + 340 pp. (Leipzig: S. Hirzel, 1939.) *RM*. 20.50.

BRUNN, A. VON. Graphische Methoden zür Lösung von Wechselstromproblemen. 8vo. 243 pp. (Basel: Benno Schwabe and Co., 1938.) 18 *Swiss francs.*

BRYANT, J. M., *M.S.*, CORRELL, J. A., *M.S.*, and JOHNSON, E. W., *M.E.* Alternating current circuits. 3rd ed. 8vo. xv + 522 pp. (New York; London: McGraw-Hill Publishing Co., Ltd., 1939.) 25*s.* (*)

BULL, H. S. Direct-current machinery. 8vo. vi + 318 pp. (New York: John Wiley and Sons, Inc.; London: Chapman and Hall, Ltd., 1939.) 15*s.* (*)

COMITÉ CONSULTATIF INTERNATIONAL TÉLÉPHONIQUE (C.C.I.F.). Proceedings of the XIth plenary meeting, Copenhagen, 11th–20th June, 1936. Translated into English. la. 4to. 388 pp. (London: The International Standard Electric Corporation, 1938.)

—— Vocabulaire téléphonique en six langues. 2e éd. la. 8vo. 441 pp. (Paris: Léon Eyrolles, 1938.) 150 *francs.*

COURAU, R. Ce qu'il faut connaître sur l'industrie électrique. 2 tom. 8vo. vi + 829 pp. (*pagin. cont.*) (Paris: J. B. Baillière et Fils, 1939.)

1, Notions générales—Production des courants industriels. 65 *francs.*
2, Centrales thermiques et hydrauliques. 100 *francs.*

CROFT, T. Practical electric illumination and signal-wiring methods. 3rd ed. Revised by G. H. Hall. 8vo. xii + 351 pp. (New York; London: McGraw-Hill Publishing Co., Ltd., 1939.) 18s. (*)

CULLWICK, E. G., *M.A.* The fundamentals of electromagnetism. With an appendix and numerous examples on the recently adopted M.K.S. system of practical units. 8vo. xxvi + 352 pp. (Cambridge: University Press, 1939.) 18s. (*)

DICKINSON, H. W. A short history of the steam engine. 8vo. xvi + 255 pp. (Cambridge: University Press [for Babcock and Wilcox, Ltd.], 1938.) 15*s.* (*)

DIESEL ENGINE. The modern diesel. High-speed compression ignition oil engines and their fuel injection systems for road and rail transport, aircraft and marine work. 5th ed. viii + 254 pp. (London: Iliffe and Sons, Ltd., 1939.) 3*s.* 6*d.* (*)

DIXON, J. L. The world of engineering. 8vo. 205 pp. (London: John Gifford, Ltd., 1939.) 8*s.* 6*d.* (*)

DOVER, A. T. Theory and practice of alternating currents. 3rd ed. General principles, circuits, instruments, measurements, transformers, machines, symmetrical components. 8vo. xvii + 591 pp. (London: Sir Isaac Pitman and Sons, Ltd., 1939.) 18s. (*)

DOWSETT, H. M. Handbook of technical instruction for wireless telegraphists. 6th ed. 8vo. xx + 624 pp. (London: Iliffe and Sons, Ltd., 1939.) (*)

EDDY, M. F. Aircraft radio. 8vo. x + 284 pp. (New York: The Ronald Press Co., 1931.) 15*s.* (*)

EVE, A. S., *C.B.E.*, *M.A.*, *F.R.S.*, and KEYS, D. A., *M.A.*, *Ph.D.* Applied geophysics in the search for minerals. 3rd ed. 8vo. x + 316 pp. (Cambridge: University Press, 1938.) 16*s.* (*)

EWING, A. W. The man of room 40: the life of Sir Alfred Ewing. 8vo. 295 pp. (London: Hutchinson & Co. (Publishers) Ltd., 1939.) 12*s.* 6*d.* (*)

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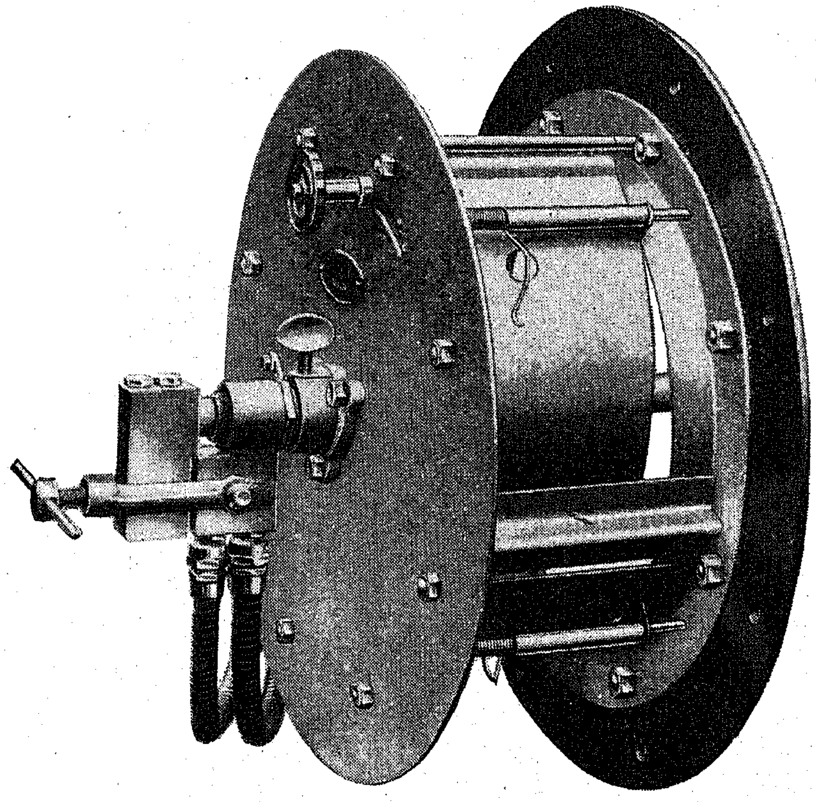

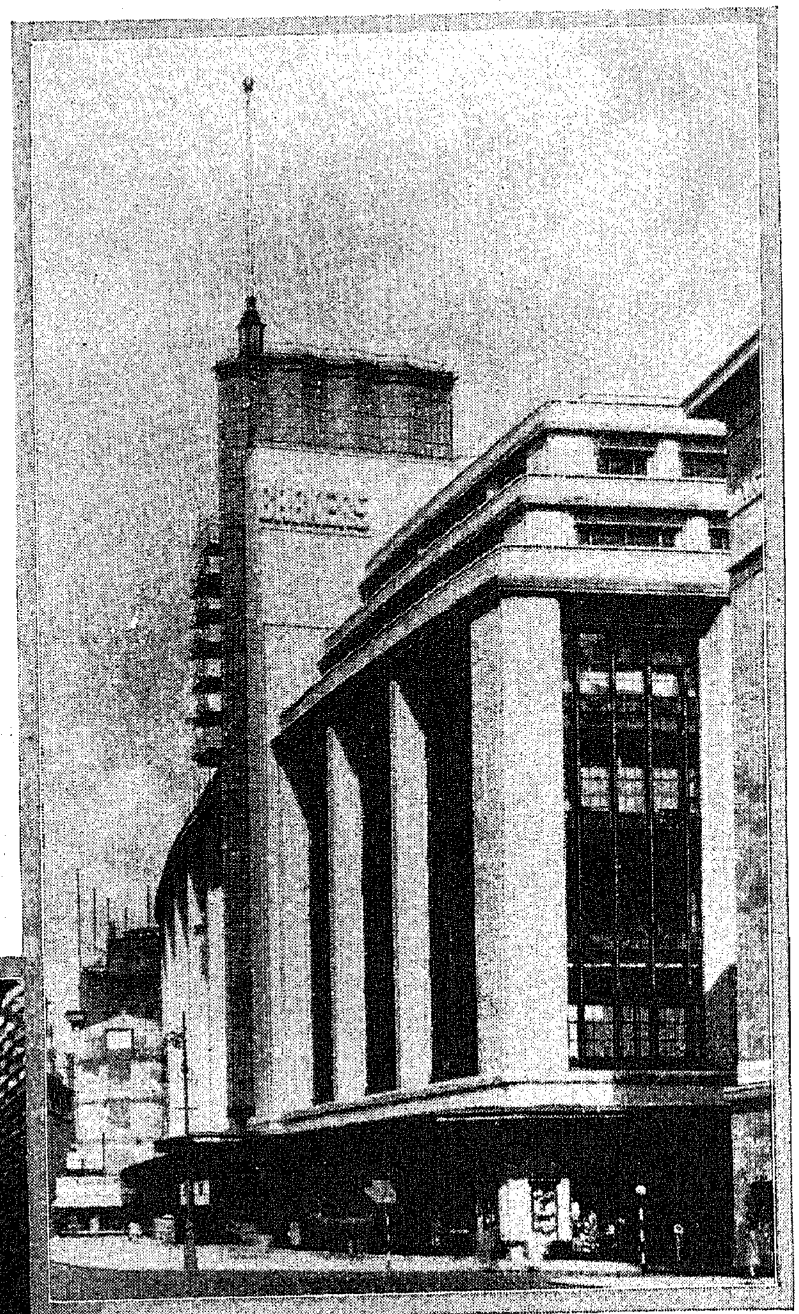

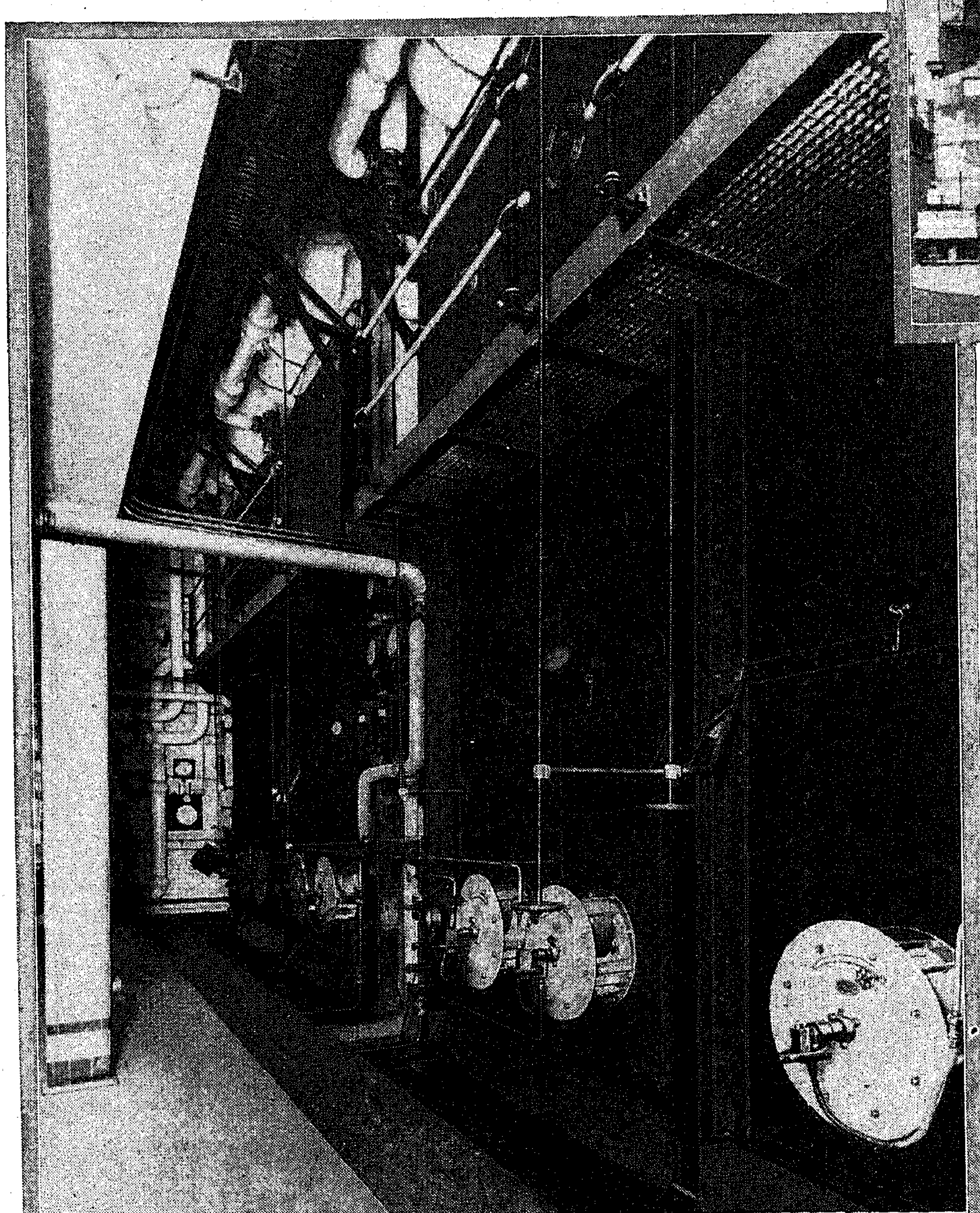

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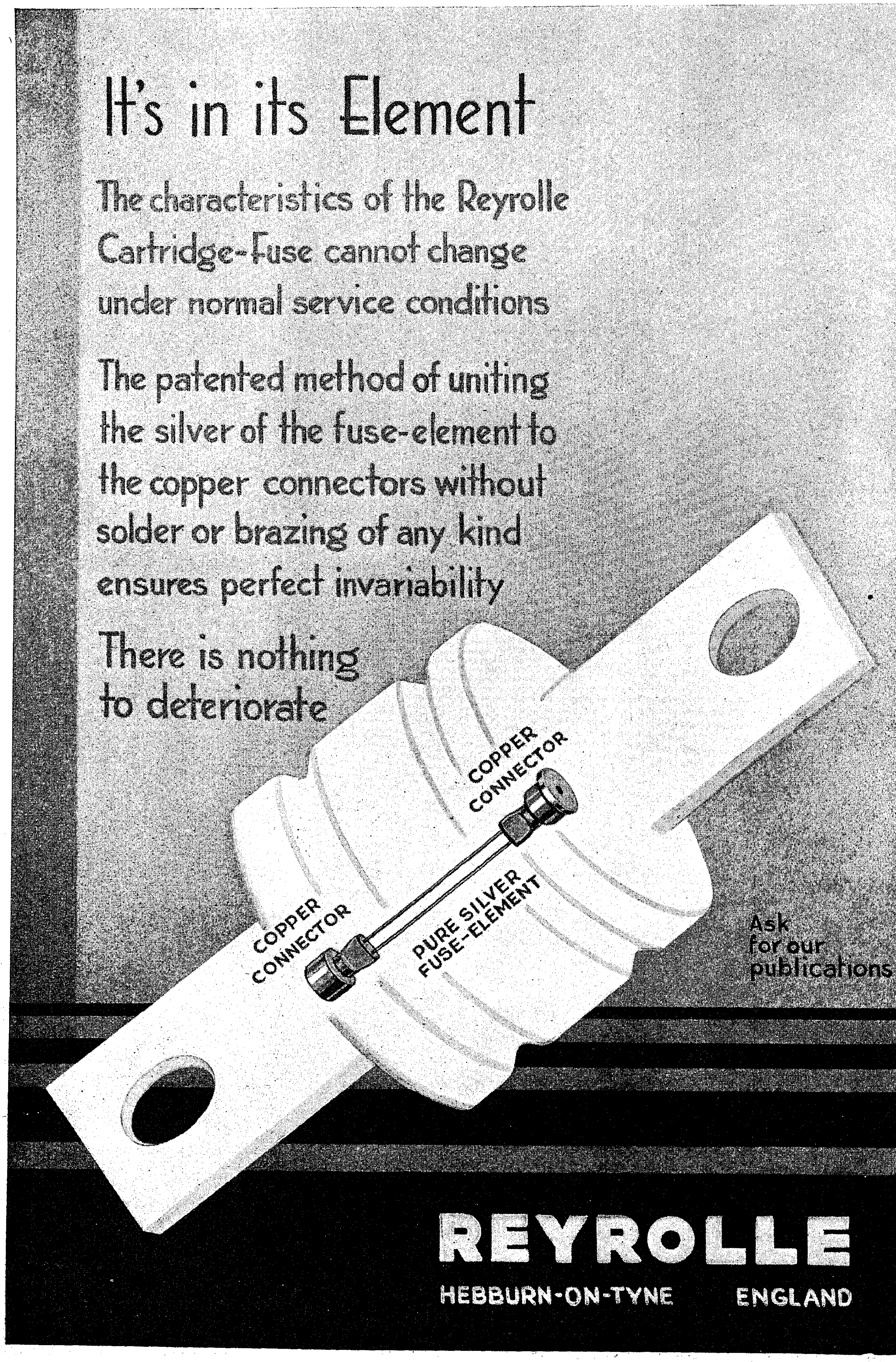
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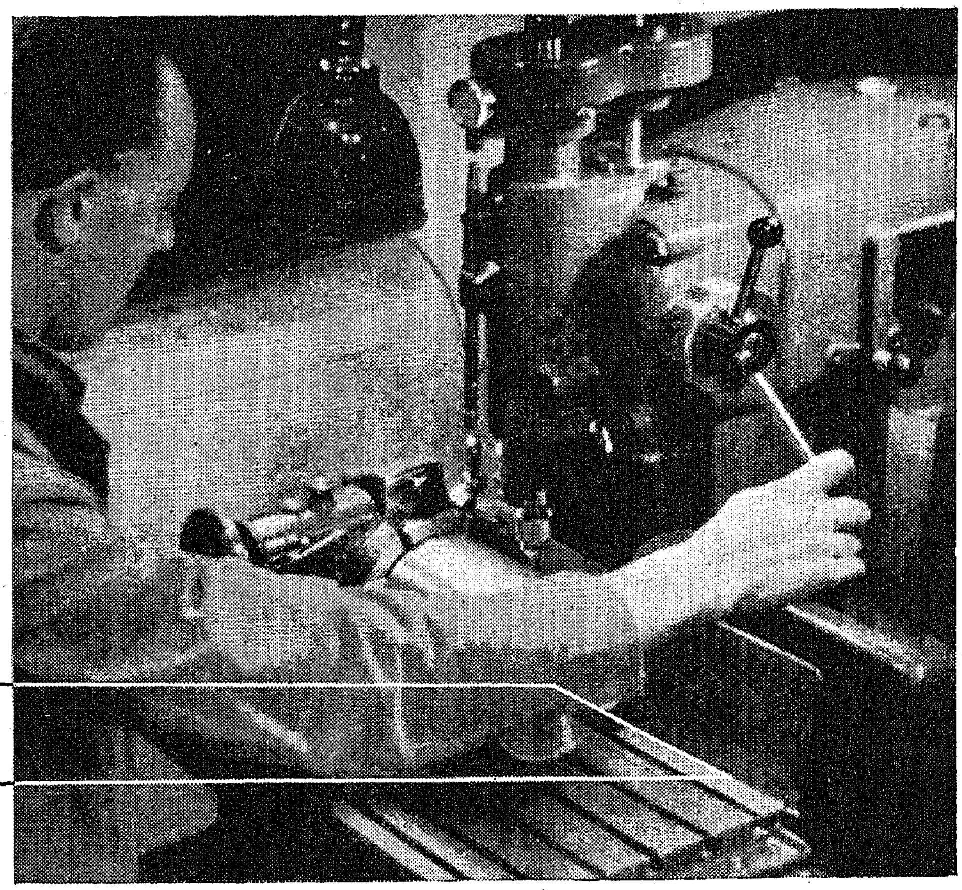

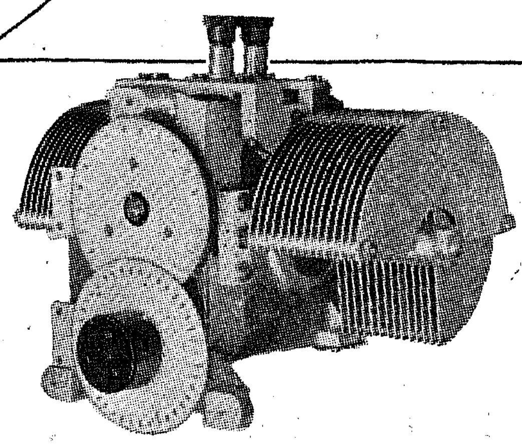

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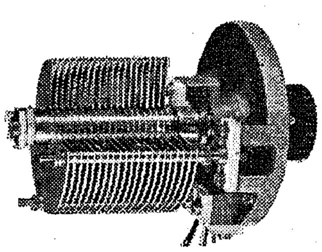

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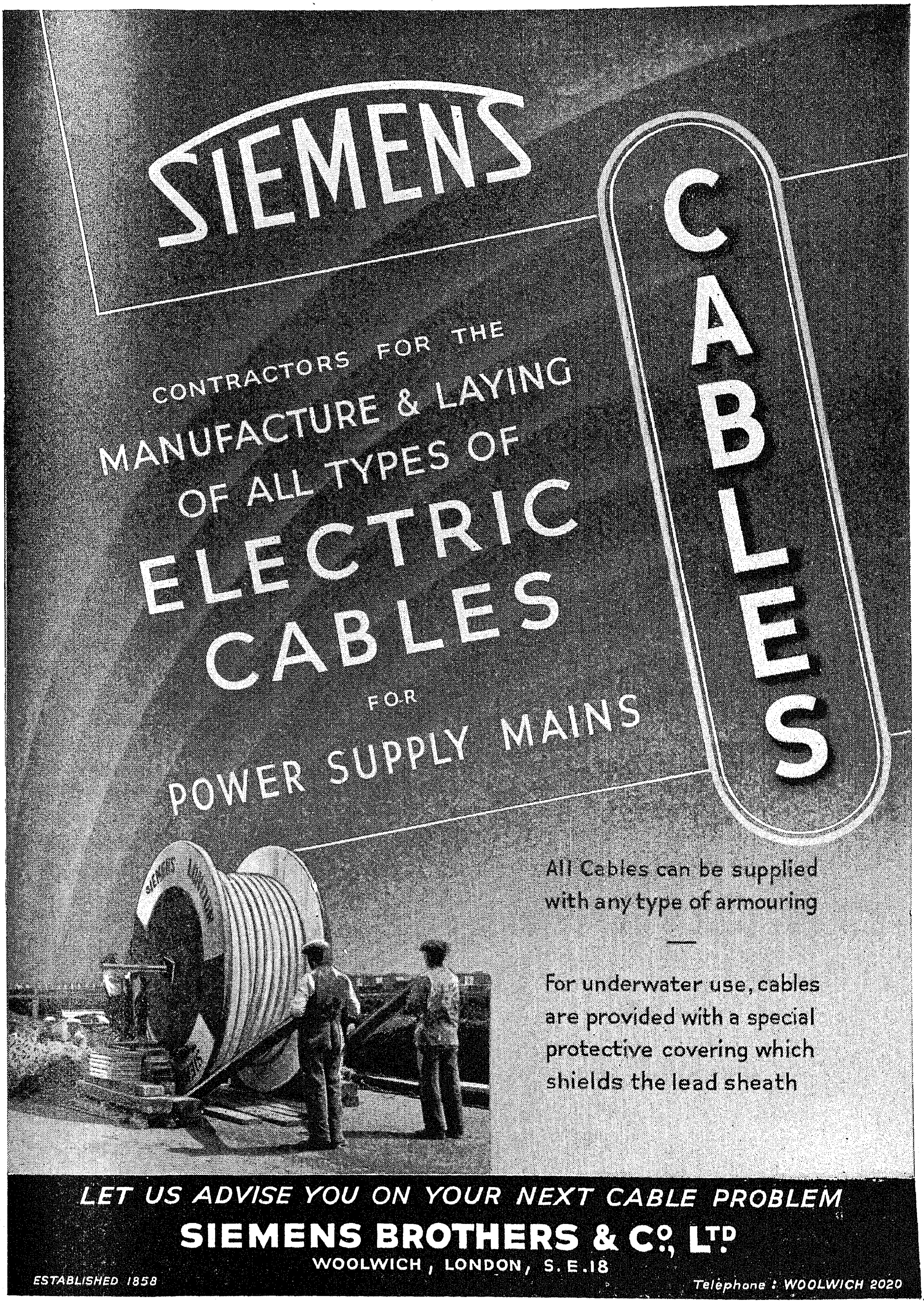
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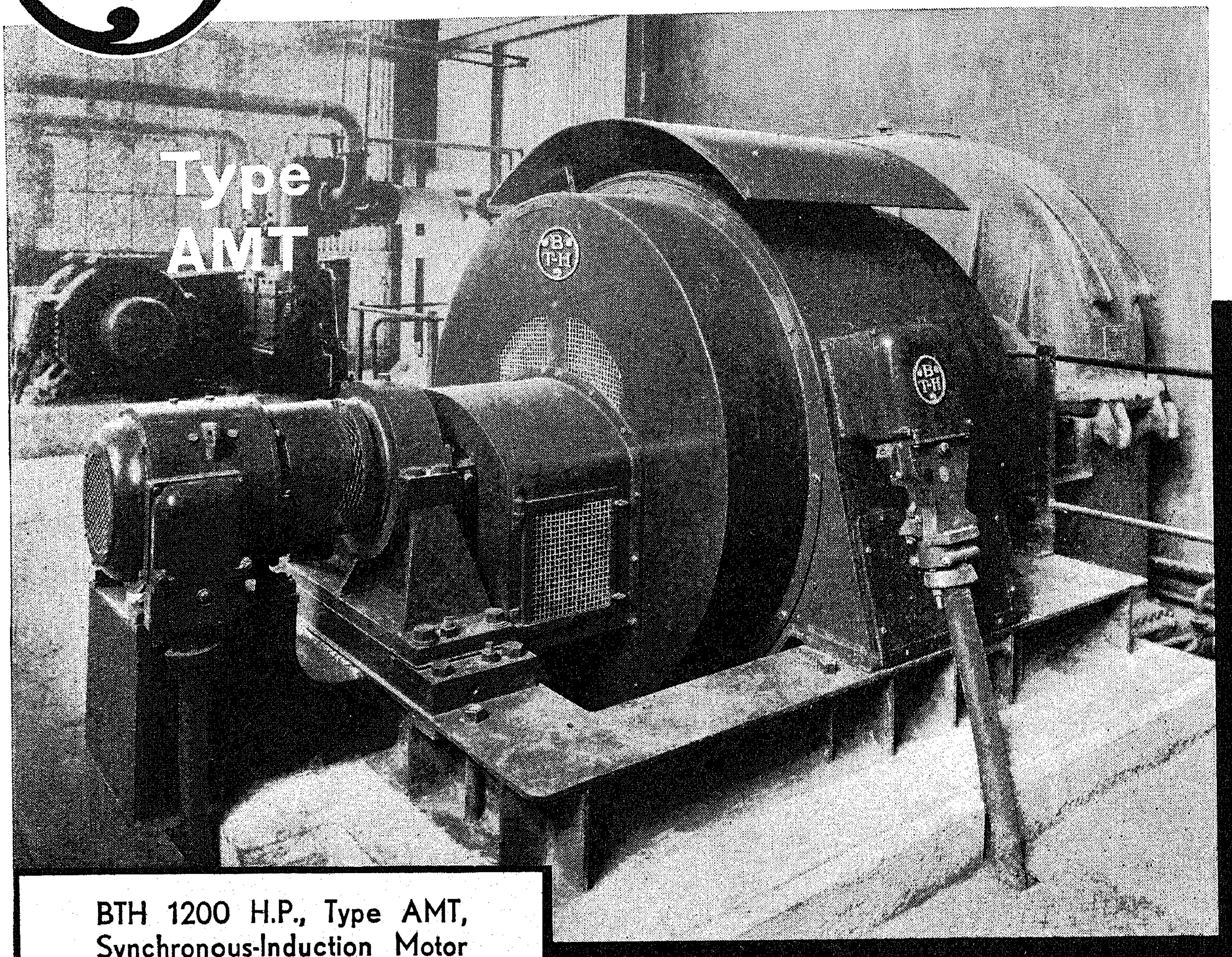

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